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Relativistic Heavy Ion Collider
Magnet Division Specification

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Class: Ancillary Specifications
Title: Nb-Ti Superconductor Wire and Cable for RHIC
Dipole and Quadrupole Magnets with 8 cm Aperture

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REVISION RECORD

Rev. No.	Date	Page	Subject	Approval	QA
A	4/23/90	Numerous	Miscellaneous Changes for RHIC Construction		
B	10/25/90	p. 17, 31	Added Fig. 1 Fixed Errors in Appendix B.		
C	6/27/91	Numerous	Miscellaneous Changes. Production RFQ Release		
D	10/9/92	Throughout	For reference, see ECN #MG00215		
E	2/16/92	6, 10	Specification changes as per ECN #MG00365		

1. Scope:

This specification establishes the requirements for the manufacture, inspection, test, identification and delivery of Nb-Ti superconductor wire fabricated into Rutherford-type cable for use in RHIC dipole and quadrupole magnets with 8 cm aperture.

The main emphasis of the specification is on adherence to a uniform production method for the conductor rather than on peak performance. The goal is to have the magnetic field behavior of all magnets in the RHIC accelerator be identical and, because of the effects of conductor magnetization and its possible time dependence, it is imperative that conductor be fabricated using materials with the same specifications and processes with the same steps, parameters and tolerances throughout each phase of the production. Therefore, production phase of the procurement will be completed by one vendor with strict adherence to that vendor's process; no process changes will be permitted during the production phase.

Wires will be selected for use in cable using critical current measurements made by the vendor. Selection will begin after a minimum amount of the production is available.

The vendor will be responsible for checking all wire dimensional, mechanical and electrical parameters and cable mechanical measurements. BNL will measure electrically all cable samples following the procedures given in Appendix B.

2. Applicable Documents:

The following documents in effect on the date of invitation to quote form a part of this specification to the extent specified herein:

- ASTM F68-82 — Standard Specification for Oxygen-Free Copper in Wrought Forms for Electron Devices - for classification requirements (Plate 1).
- ASTM B170-89 — Standard Specification for Oxygen-Free Electrolytic Copper-Refinery Shapes - chemistry requirements governed by B170, Grade 1.
- RHIC-MAG-M-4000 — Niobium-Titanium Alloy Bars and Rods
- RHIC-MAG-M-4001 — Barrier Grade Niobium Sheet
- RHIC-MAG-M-4135 — RHIC Superconductor Wire Twist Measurement
- RHIC-MAG-M-7142 — RHIC 8cm Dipole/Quadrupole Cable Test Methods

- BNL-QA-101 Brookhaven National Laboratory Seller Quality Assurance Requirements
- MIL-I-45208A Inspection System Requirements
- MIL-STD-45662 Calibration Systems Requirements
- BNL Dwg. 12000001 Superconductor Keystoned Cable

3. Requirements:

3.1 Raw Material: Raw material used in the manufacture of RHIC Nb-Ti composite wire shall be procured to the applicable requirements of this specification and inspected/tested by the vendor for conformance to those requirements before release for production use.

3.1.1 Nonconforming Raw Material: Material found to deviate from requirements shall not be dispositioned through any seller review process for production use without prior, specific written approval from BNL.

3.1.2 Raw Material Identification: Each lot of wire raw material shall be uniquely identified to allow all vendor manufacturing, test, and inspection records for finished wire to be traceable to the original lot of raw material. Using the Cable Map there must be traceability from the cable to the wire; see paragraph 3.2.5.16.

3.2 Technical Properties

3.2.1 Conductor Type: The conductor shall be a composite of Nb-Ti filaments in an oxygen-free copper matrix.

3.2.2 Conductor Billet Components: The components described below shall be used to fabricate the superconductor.

3.2.2.1 Niobium-Titanium Alloy: The alloy composition shall be Nb 47 $\pm$ 1 wt. % Ti, and shall be high homogeneity grade or BNL-approved equivalent. This tolerance on Ti content covers all Nb-Ti bars to be used to fill the order. It must be purchased by the vendor to meet the requirements of the specification RHIC-MAG-M-4000.

3.2.2.2 Copper: With the exception of the billet end caps, all copper raw material purchased by the vendor to be used for billet fabrication shall meet the chemistry requirements of ASTM B170-89 - Grade 1, and have residual resistance ratio (RRR) greater than 250:1. This copper, when finally used for the billet cans, shall be wrought, not cast, and shall meet the classification requirements of ASTM F68-82, Class 2 or better. The copper used for the billet end caps shall be wrought, not cast.

3.2.2.3 Niobium Material for Diffusion Barrier Construction: Niobium must be purchased by the vendor to meet the requirements of the specification RHIC-MAG-M-4001.

3.2.3 Conductor Fabrication: The procedures listed below must be followed during billet assembly or processing and cabling.

3.2.3.1 Monofilament Shape: The monofilament rods used to assemble the multifilament billet shall have hexagonal cross section.

3.2.3.2 Diffusion Barrier Construction: A niobium diffusion barrier shall be placed between the Nb-Ti and the copper in the monofilament billet. Its thickness and quality shall be sufficient to prevent formation of copper-titanium compounds during wire fabrication.

3.2.3.3 Filament Array: The design of the overall placement of filaments inside the billet shall be submitted to BNL for approval with the bid package. There shall be a copper island in the center of the billet; it shall comprise a minimum of 10% of the total area of the final wire.

3.2.3.4 State of Wire Anneal: The ductility of the wire or the state of copper anneal is to be determined by the vendor to produce mechanically uniform cable while also satisfying the other requirements.

3.2.3.5 Production With No Deviations: The specification for Nb-Ti, copper and Nb materials used for wire manufacturing shall be the same throughout the production. Also, the production steps, parameters and tolerances for the wire and cable fabrication shall remain the same during the production phase.

3.2.3.6 Production Unit: All superconductor wire produced to this specification shall be processed in "production units".

A "production unit" consists of material from a common multifilament billet which undergoes identical mechanical and thermal processing, and shall be identified as such. A "production unit" may be less than one full billet. All material from a "production unit" shall be thermally cycled together in the same furnace, for each and every heat-treatment.

Work-In-Process material from a "production unit" shall remain physically grouped together throughout all phases of the manufacturing process. Any portion of a billet which becomes separated from its "production unit" shall be considered non-conforming and shall be addressed as such.

3.2.3.7 Control of Manufacturing Machines and Methods: The machines and equipment used to process all superconductor made to this specification shall be identified for BNL and documented as part of the vendor's Quality Plan. No changes to machines, methods or processes shall be permitted without prior written approval of BNL.

3.2.3.8 Wire Selection for Cable: The percent of wire utilization for cabling will never exceed 50% in any month in the early stages of the contract. It will increase predictably towards contract completion. The purpose is to allow production of sufficient material to allow a meaningful wire selection process for cables. All wire samples will be identified by critical current at 5.0T (paragraph 3.2.4.10), and then selected by the vendor for use in cable. Any wire spools not measured shall be identified by the average of the measurements of other wire spools in the same "production unit"; see Appendix A. This procedure will be reviewed regularly by BNL during production. Wire selection shall be as follows. The sum of the critical currents for the wire used in each cable length may not vary by more than ± 2% maximum limit from the running average.

3.2.3.9 Frequency of Sample Testing: The expected frequency of wire and cable sample testing by the vendor and by BNL is summarized in Appendix A. The transmittal of the data and samples to BNL is given in paragraphs 4.2, 4.4, 4.5 and 5.4 for the wire and cable.

3.2.3.10 Manufacturing Data: BNL does not require regular transmittal of manufacturing data related to wire and cable fabrication. These data will be audited regularly by BNL staff at the vendor facility. The vendor must maintain manufacturing data records for two (2) years after the date of acceptance of the cable by BNL.

3.2.4 Wire Performance Requirements: The superconductor wire must meet the performance requirements described in Tables I and II and explained in subsequent paragraphs. Checks of the wire dimensional, mechanical and electrical requirements are the responsibility of the vendor. One 10 ft. long wire test specimen, which is adjacent to the location used for each vendor wire electrical test, shall be delivered to BNL; see paragraph 4.5. The frequency of wire sample testing is given in Appendix A.

Table I. Wire Dimensional and Mechanical Requirements

Requirement	Value	Defined in Para. No.
Nominal Filament Diameter	6μm	3.2.4.1
Nominal Filament Spacing	>1μm	3.2.4.1
Nominal Copper-to-Non-Copper Ratio	(2.25 ± 0.1):1	3.2.4.2
Number of Filaments	(3510) ± 20	3.2.4.3
Wire Diameter	0.0255 ± 0.0001 in.	3.2.4.4
Wire Twist Direction	Right	3.2.4.5
Wire Twist Pitch	1.9 ± 0.2 twists/in.	3.2.4.5 & RHIC-MAG-M-4135
Wire Sharp Bend Test	No Damage	3.2.4.6 & Test Method 4141-1, App. B
Wire Springback Test	<1090 degrees (horiz.) <1200 degrees (vert.)	3.2.4.7 & Test Method 4141-2, App. B
Wire Surface Condition	No defects	3.2.4.8
Wire Minimum Length	2,200 ft.	3.2.4.9

Table II. Wire Electrical Requirements

Requirement	Value	Defined in Para. No.
Wire Minimum Critical Current at 5.0T	264A	3.2.4.10, 3.2.4.11
Variation of Measured Wire Critical Current at 5.0T	± 10% maximum limit	3.2.4.10, 3.2.4.12
Wire Maximum Critical Current at 3.0T	1.6 times measured critical current at 5.0T	3.2.4.10, 3.2.4.13 and Test Method 4141-3, App. B
Wire Maximum R(295)	0.0765 ohms/m	3.2.4.14 and Test Method 4141-3, App. B
Wire Minimum RRR	38	3.2.4.14 and Test Method 4141-3, App. B

3.2.4.1 Nominal Filament Diameter and Spacing: The nominal filament diameter and spacing shall be defined by the billet design. Before fabrication, the vendor shall submit to BNL for written approval a drawing showing the billet assembly and dimensions to demonstrate that the nominal filament diameter and spacing shall be obtained at the final wire size. Shaving of the external copper during billet processing must be considered in the demonstration.

3.2.4.2 Nominal Copper-to-Non-Copper Ratio: The nominal value of the ratio of copper volume to non-copper volume is 2.25:1. However, to simplify measurement there is no technical requirement for this parameter. Instead there will be a technical requirement for R(295), for RRR and for the wire diameter. The calculated copper-to-non-copper ratio will be greater than 2.15:1 provided that the wire diameter is within the specified tolerance, R(295) is less than a maximum and RRR is greater than a minimum value. The procedure for determining this ratio by electrical measurement will be finalized when R(295) and RRR are known from the state of the wire anneal. See Appendix B for a description of this method.

3.2.4.3 Number of Filaments: The vendor shall choose the number of filaments for the RHIC production to be within the range specified in Table I. This chosen number shall remain fixed throughout the production within the specified tolerance.

3.2.4.4 Wire Diameter: The tolerance on the wire diameter is a maximum limit and does not include averaging or statistical weighing. The tolerance must be held for the wire measured across any diameter/axis. Verification of this diameter shall be determined by the vendor using an appropriately calibrated laser micrometer used to check all of the wire produced. The laser micrometer should be capable of detecting local variations in the wire diameter over a length of 1/2-inch. Statistical analysis of laser micrometer measurements shall be provided by the vendor to BNL.

3.2.4.5 Wire Twist Direction and Pitch: All wire shall be right-twist so the filaments follow the same rotation as a right-hand screw thread. The wire is to be twisted before the final sizing die. Requirements on twisting shall apply over the full length of the delivered wire. No leaders with variable twist are allowed. Wire twist measurements shall be done as described in RHIC-MAG-M-4135. The tooling is the responsibility of the vendor.

3.2.4.6 Wire Sharp Bend Test: The superconductor wire shall meet the sharp bend test requirements with no visible damage to the copper or to the filaments after etching. The test procedure is described in Appendix B.

3.2.4.7 Wire Springback Test: The superconductor wire shall meet the requirements of a springback test following the test procedure described in Appendix B, with the fixture mounted on a horizontal surface. If the fixture is mounted on a vertical surface, with wire and weight hanging freely, the maximum acceptable value shall be as given in Table I.

3.2.4.8 Wire Surface Condition: The wire surface shall be free of all surface defects, slivers, folds, laminations, dirt, or inclusions. No filaments shall be visible. These conditions must be met for any sample of the wire inspected using a magnification of 10x.

3.2.4.9 Wire Minimum Length: A minimum length requirement is imposed to assure high quality of the wire and its fabrication process. Length shall be determined after all lead and end defects have been removed by cropping. These defects include areas of distorted cross section due to wire pointing by swaging, foreign material attached as a temporary leader, or areas of distorted filaments that occur at the start and end of an extrusion. A continuous compilation of wire lengths must be made by the vendor and available to BNL on request.

3.2.4.10 Wire Critical Current Determination: The critical current values refer to a test temperature of [(4.22 ± 0.01)K] and a critical current criterion of $\rho = 1 \times 10^{-14}$ ohm • m, based on the wire cross section area and with the applied magnetic field (given in Table II) perpendicular to the wire axis. The tolerance on the magnetic field is ± 0.01T. No correction is made for self-field effects. The critical current test procedure given in Appendix B is to be used. Although it is not included as a technical requirement, the Quality Index x (n) is to be reported by the vendor with every critical current measurement. This parameter is described in Appendix B. It is required that under the test conditions the quench current, I_Q, be greater than the critical current. I_c at 1×10^{-13} ohm • m is also to be reported by the vendor in lieu of determining I_Q.

3.2.4.11 Wire Minimum Critical Current at 5.0T: The wire minimum critical current in Table II and the conditions defined in paragraph 3.2.4.10 correspond to a current density in the non-copper region of the wire of 2600 A/mm^2 at 5.0T, 4.22K, a nominal copper-to-non-copper ratio of 2.25:1 and a wire diameter of 0.0255 in. No correction is made for self-field effects. Any wire not meeting this requirement will be rejected.

3.2.4.12 Variation of Measured Wire Critical Current at 5.0T: The variation of the measured wire critical current at 5.0T shall remain within the given maximum limit from the running average throughout the entire production of each phase. Any wire with critical current outside this range will be rejected.

3.2.4.13 Wire Maximum Critical Current at 3.0T: This maximum value is given to provide an upper limit to the low field J_c and the amount of superconductor magnetization.

3.2.4.14 Wire Maximum R(295) and Minimum RRR: The resistance of the wire at room temperature [(295.0 ± 0.2)K] is frequently referred to as the normal state resistance. It is an important parameter for magnet construction and depends primarily on the content and purity of the copper. The procedure for measuring R(295) described in Appendix B is to be used.

The resistance of the wire just above the Nb-Ti superconductor transition temperature and at zero field is termed R(10). The procedure for measuring R(10) described in Appendix B is to be used. The wire residual resistance ratio or RRR is given by the ratio R(295)/R(10).

3.2.5 Cable Performance Requirements: The superconductor cable must meet the performance requirements described in Tables III and IV and explained in subsequent paragraphs. Checks of the cable dimensional and mechanical requirements are the responsibility of the vendor. An exception to this is periodic off-line checks of the cable keystone angle; see paragraph 3.2.5.4. Checks of the cable electrical requirements are the responsibility of BNL and will be made using the 24 ft.-long Preshipment Cable Test Specimen; see paragraph 5.4. The frequency of cable sample testing is given in Appendix A.

Table III. Cable Dimensional and Mechanical Requirements.

Requirement	Value	Defined in Para. No.
Number of Wires in Cable	30	--
Cable Mid-Thickness	0.04590 ± 0.00025 in.	3.2.5.1, 3.2.5.2
Cable Width	0.383 ± 0.001 in.	3.2.5.1, 3.2.5.3
Cable Keystone Angle	1.2 ± 0.1 degrees	3.2.5.1, 3.2.5.4
Cable Lay Direction	Left	3.2.5.5
Cable Lay Pitch	2.9 ± 0.2 in.	3.2.5.5
Wire Twist Pitch in Cable	1.9 ± 0.2 twists/in.	3.2.5.6 and RHIC-MAG-M-4135
Maximum Cable Residual Twist	+ 120 degrees	3.2.5.7 and RHIC-MAG-M-7142
Cable Bend Test	No Damage	3.2.5.8 and RHIC-MAG-M-7142
Cable Filament Condition	No Damage	3.2.5.9 and RHIC-MAG-M-7142
Cable Surface Condition	Clean and free from chips, roughness, sharp edges or burrs; surface uniform to < 25% of a single wire diameter; no broken wires or crossovers.	3.2.5.10
Cable Lengths	Maximum length on a spool: 15,000 ft.	3.2.5.11

Table IV. Cable Electrical Requirements.

Requirement	Value	Defined in Para. No.
Cable Minimum Critical Current at 5.0T	7524A	3.2.5.12, 3.2.5.13 and Test Method 4141-4, App. B
Variation of Measured Cable Critical current at 5.0T	± 6% maximum limit	3.2.5.12, 3.2.5.14, 3.2.5.15 and Test Method 4141-4, App. B
Cable Maximum R(295)	0.00268 ohms/m	3.2.5.15 and Test Method 4141-4, App. B
Cable Minimum RRR	38	3.2.5.15 and Test Method 4141-4, App. B

3.2.5.1 Cable Dimensions: The primary measurements of the cable mid-thickness, width and keystone angle are to be made with a Cable Measuring Machine (CMM) calibrated to a BNL-approved, certified reference standard. The measurements shall be given to BNL on PC- compatible 3-1/2 or 5-1/4 in. diameter floppy disc.

The Cable Measuring Machine is a computer controlled device which continuously measures these dimensions at variable, discrete positions under a stress of (5,000 ± 40) psi. The machine is calibrated against a certified reference standard at the beginning of a run. Normally it is placed in the production line following the cabling machine and monitors the dimensions of the cable so the tolerances given in Table III can be achieved. The tension on the cable when measurements are made by the CMM must be less than 60 lb. The machine can be produced commercially. Documentation and plans are available from the Magnet Systems Division of the SSC Laboratory. Availability of this machine for the RHIC production is the responsibility of the vendor.

3.2.5.2 Cable Mid-Thickness: Mid-thickness measurements provided by the Cable Measuring Machine shall be checked periodically off-line using a ten-stack measuring fixture. The tooling and methods to make the ten-stack measurement are described in RHIC-MAG-M-7142. A ten-stack measuring fixture will be provided by BNL to the vendor. Ten-stack measurements are to be done to check for consistency of the CMM. Correlation of measurements with CMM data is expected to be within ± 0.3 mils.

3.2.5.3 Cable Width: Width measurements provided by the Cable Measuring Machine shall be considered as the primary measurement. No off-line checks are necessary.

3.2.5.4 Cable Keystone Angle: Keystone angle measurements provided by the Cable Measuring Machine shall be checked periodically off-line with the cable under (40 ± 2) lb. tension and mounted in the Cable Keystone Measurement Fixture. The tooling and methods to make this measurement are described in RHIC-MAG-M-7142. Because of the uniqueness of this fixture, checks of this angle will be made by BNL using the Preshipment Cable Test Specimen provided by the vendor.

3.2.5.5 Cable Lay Direction and Pitch: All cable is to be fabricated as left lay so the wires follow the same rotation as a left-hand screw thread. When the cable lay is opposite to the wire twist direction, this will reduce the amount of residual twist in the cable which is a necessary characteristic for conductor to produce satisfactory coils. The cable lay pitch is to be measured parallel to the cable edge. Once a value of Cable Lay Pitch is chosen, it shall not vary during production to the measurement accuracy of this parameter which will be less than 0.1 inch.

3.2.5.6 Wire Twist Pitch in Cable: Since some cabling machines can add or remove wire twist during cabling, it is necessary to define this parameter. For RHIC 30-strand cable the wire twist shall not be altered during cabling. Therefore, a cabling machine with simple planetary operation is required. The twist measurements shall be done as described in RHIC-MAG-M-4135. The tooling is the responsibility of the vendor.

3.2.5.7 Cable Residual Twist: The cable shall not have excessive twist. A check is made on the twist by using the Cable Twist Measurement Fixture. The cable tension during measurement shall be (40 ± 2) lb. The tooling and methods to make this measurement are described in RHIC-MAG-M-7142. The tooling is the responsibility of the vendor. The direction of twist must be recorded with the following convention: positive (+) is clockwise when looking down onto a vertically hanging cable sample.

3.2.5.8 Cable Bend Test: The purpose of the test is to check the cable resistance to bend-induced cracks and fractures. A cable sample is to be bent over a (0.50 ± 0.01) in.-diameter pin while applying a (40 ± 2) lb. tensile load. Visual inspection under a magnification of 10x must show no visual damage to the wires. The bent cable sample shall be straightened and acid etched. It is again inspected in like manner to look for filament damage at the bend. The tooling and methods to make this measurement are described in RHIC-MAG-M-7142. The tooling is the responsibility of the vendor.

3.2.5.9 Cable Filament Condition: The condition of the Nb-Ti filaments in individual wires must not show excessive breakage as a result of the cabling process. After acid etching of an unbent (nominally straight) cable sample, it is inspected under a magnification of 10x. For example, clumps of broken filaments usually at the cable edge, or > 5% general breakage in any wire, is indication of excessive damage and would be cause for rejection of the cable by BNL.

3.2.5.10 Cable Surface Condition: As delivered to BNL, the cable surface must be thoroughly clean and free from metallic particles or residue. A small amount of residual oil from the wire or cable fabrication is permitted, provided that it can be removed in the BNL ultrasonic degreasing bath installed on the cable insulating line. This bath uses Trichloroethane as a degreasing solution. The cable must be free of roughness, sharp edges or burrs that could damage insulation material, and it must be compacted in a stable, uniform manner. In order to avoid "popped wires", it is required that the top surfaces of adjacent wires (forming the wide surface of the cable) lie in the same plane to within 25% of a single wire diameter. This condition should be met when the cable is laid flat with minimal (<2 lb.) tension applied. There shall be no broken wires or crossovers of wires in the cable.

3.2.5.11 Cable Lengths: The total amount of the actual cable order and the exact piece lengths will be given in the purchase order. Length of cable fabricated must be determined with tension <60 lb. The cable lengths given in Table III represent the longest and shortest lengths expected to be produced by the vendor and are as measured on the cabling machine at the location of the CMM. The amounts given do not include the Preshipment Cable Test Specimens described in paragraph 5.4 and Appendix A. All leaders used for cabling setup and which do not meet the cable requirements must be cut off and discarded.

The following conditions apply to the length of cable produced:

- The maximum amount of cable on a spool will be 15,000 ft.
- Only fully conforming cable shall be shipped to BNL; all non-conformances must be removed by the vendor.
- Based on a production length of cable (< 15,000 ft.) and the purchase order, the vendor shall propose cutting the cable. These "Cut Diagrams" shall be identified with the spool number and

submitted to BNL. No cutting of cable or separation will be required by the vendor.

- Short lengths of cable may be spliced together so several lengths of cable may be stored and transported on a single spool. The method of splicing and marking the splice joints must be approved by BNL. A diagram must be provided by the vendor to show clearly the sequence of cable lengths on the spool. No cold weld splices are allowed on delivered spools.

3.2.5.12 Cable Critical Current Determination: The critical current values refer to a temperature of [(4.22 $\pm$ 0.1)K] and a critical current criterion of $\rho = 1\mathrm{x}10^{-14}$ ohm ● m across the entire cable cross section. The applied magnetic field is perpendicular to the wide surface of the cable. The tolerance on the magnetic field is less than $\pm$ 0.01T. A correction is made for self-field effects and the required field value is obtained at the narrow edge of the cable. The critical current test procedure to be used by BNL is given in Appendix B. Although it is not included as a technical requirement, the Quality Index (n) will be determined by BNL for every critical current measurement. This parameter is described in Appendix B. It is required that under the test conditions the quench current, I_Q, be greater than the critical current. I_Q is also to be reported.

3.2.5.13 Cable Minimum Critical Current at 5.0T: The basis for the derivation of the cable minimum critical current can be calculated from the "Wire Minimum Critical Current at 5.0T" given in Table II times 30 (Number of Wires in Cable), and multiplying by 0.95 (also see paragraphs 3.2.4.10 and 3.2.4.11).

3.2.5.14 Variation of Measured Cable Critical Current at 5.0T: The variation of the measured cable critical current at 5.0T shall remain within the given maximum limit from the running average throughout the entire production of each phase.

3.2.5.15 Cable Maximum R(295) and Minimum RRR: The resistance of the cable at room temperature [(295.0 $\pm$ 0.2)K] and the residual resistance ratio (RRR), given by the ratio R(295)/R(10), will be determined by BNL following the procedures given in Appendix B.

3.2.5.16 Cable Map: The vendor shall supply a "Cable Map" giving the serial numbers of the wires used in the cable manufacturing and the sum of the critical currents for the wires used in the cable based on vendor wire electrical measurements; see paragraph 3.2.3.8.

3.2.5.17 Cold Welds: The cable lengths in conformance with this specification shall have no cold welds.

3.2.5.17.1 If the vendor decides to follow a practice of placing cold welds in the wire spools during cabling and subsequently removing the corresponding sections of cable, there must be extremely careful quality control to assure that the appropriate regions of the cable are identified and removed. The vendor's Quality Assurance program must address the removal of cold welds from the cable.

4. Quality Assurance Provisions:

The vendor shall maintain a quality assurance program to insure that each item offered for acceptance or approval conforms to the requirements herein.

4.1 Requirements of BNL-QA-101

4.1.1 The vendor shall accomplish the following requirements of BNL-QA-101, Brookhaven National Laboratory Seller Quality Assurance Requirements:

3.1	including 3.1.2 or the Note following 3.1.3.
3.2	Audits may be performed by BNL at any time.
3.3	
3.4	
3.5	
3.6	
3.7	see MIL-STD-45662
4.1	
4.2	
4.3	
4.4	including 4.4.1, 4.4.2, 4.4.3, 4.4.4 but 30 days before first billet assembly
4.5	
4.6	but 30 days before first billet assembly
4.7	including 4.7.1, and 4.7.2 to be held in file.
4.9	
4.10	including 4.10.1, 4.10.2, 4.10.3, 4.10.4, 4.10.5
4.12	see para. 5.4 of RHIC-MAG-M-4141

4.13	
4.15	
4.18	including 4.18.2 and 4.18.4
4.19	but no changes allowed
4.21	
4.23	
4.35	for the Cable Meas. Machine (CMM), etc.
4.37	for the Cable Meas. Machine (CMM), etc.

4.1.2 BNL does not grant the Seller material review authority to accept as-is items that do not conform to the requirements of this procurement, or to repair items to a still nonconforming condition.

4.1.3 In the event of conflict between this specification and BNL-QA-101, this specification shall take precedence.

4.2 Data Transmittal: The vendor shall complete and submit to BNL wire and cable measurement data as given in Appendix C. Electronic data transmittal to BNL is required. An acceptable format will be developed by BNL and the vendor.

4.3 Statistical Process Control: The vendor and BNL shall use Statistical Process Control to study the manufacturing parameters of the RHIC wire and cable.

4.4 Wire Measurement Data and Samples: The frequency of wire measurements is given in Appendix A. The data shall be submitted in electronic form to BNL for information purposes approximately one week in advance of the cable production.

4.5 Wire Samples: Ten ft.-long wire samples will be taken from every wire spool and sent to BNL. If that wire spool is one of those selected by the vendor for measurements as described in Appendix A, the sample shall be taken adjacent to the location used for each vendor wire electrical test. Envelopes and labels for the wire samples will be provided by BNL.

5. Preparation for Delivery:

5.1 Packaging: Spools of cable shall be packaged and secured to pallets to assure adequate protection against dirt, chips and handling damage.

5.2 Reels/Spools: The cable must be spooled on BNL-approved reels with a minimum hub diameter of 24 inches. The spools must be constructed to prevent damage to the cable during spooling and unspooling. The spools shall be boxed or strapped to a pallet and protected to prevent damage during shipment and handling. They must be stacked and shipped with the spool flanges maintained in a vertical orientation (axes horizontal) in order to prevent the cable from settling on the spool.

5.3 Winding Requirements: During fabrication or transport, the cable must be wound so there are no crossovers of the cable windings. Filler cord shall be used at the reel flanges as required so the cable will lie flat. For required winding direction, see Fig. 1.

5.4 Preshipment Cable Test Specimen Submittal: The vendor shall deliver to BNL 24 ft.-long samples of cable from one end of every continuous length of cable or a minimum of one sample every 15,000 ft. Each sample must be adjacent to one used by the vendor to verify the cable dimensional and mechanical requirements by off-line measurement. Sample identification shall include "Preshipment Cable Test Specimen" and the information required by paragraph number 5.6. These samples shall be individually marked with their serial numbers and identified as coming from either hub or lead end of cable spool, and shipped to BNL within seven working days of manufacture of the cable and ahead of the regular cable shipment. The cable samples must be accompanied by results of mechanical measurements made during the cabling operation and by the off-line tests made by the vendor. A Cable Map must accompany these results. Cable samples must be degreased and cleaned by the vendor prior to shipment. Level of cleanliness and cleaning process proposed by the vendor must be approved by BNL. The samples shall be shipped to BNL wound on a spool of minimum 12-inch hub diameter in a manner so they will not be damaged. These samples will be used by BNL to verify the mechanical and electrical requirements of the cable while production is in progress. It is important that they arrive at BNL rapidly so there is minimal continued production before verification of Cable Test Specimens.

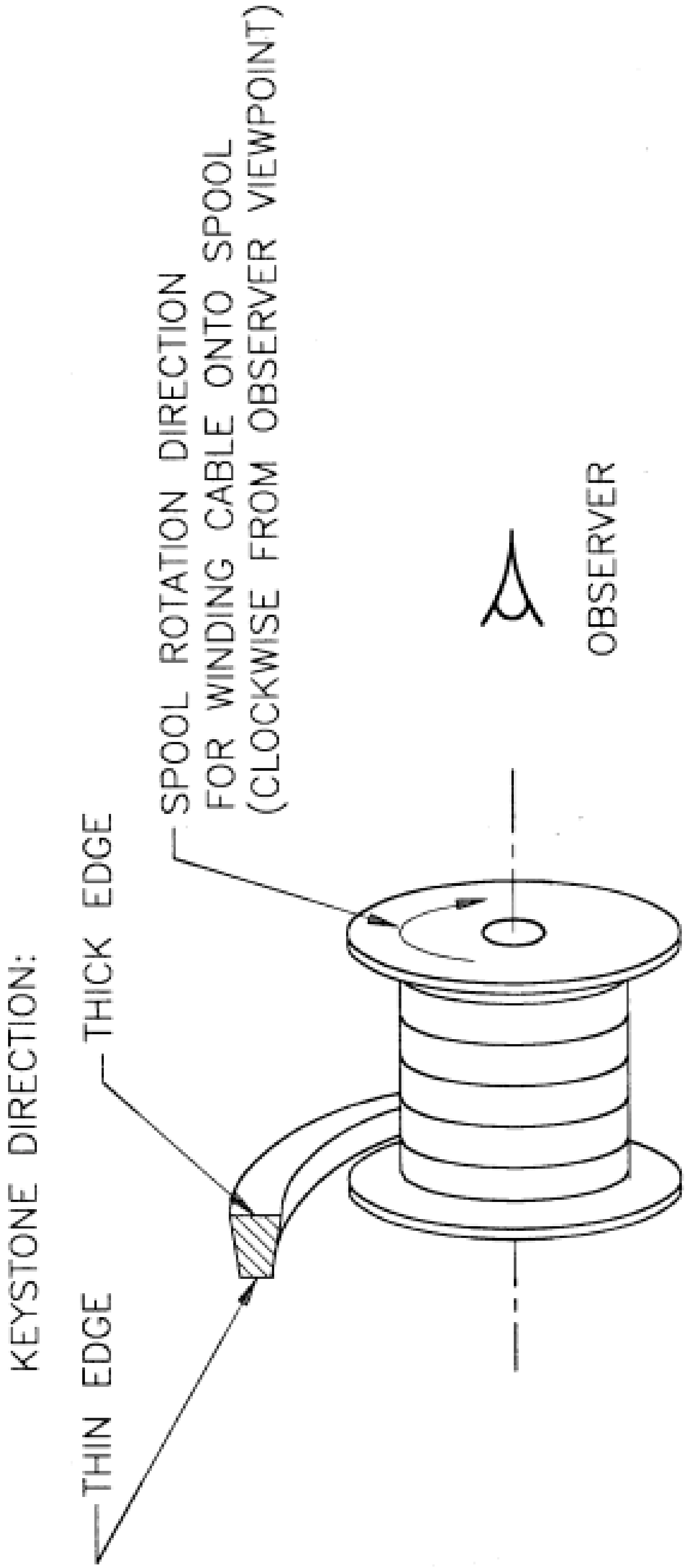
5.5 Coordination of Cable Lengths: The vendor shall develop a standard system to be approved by BNL for coordination of cable length information so there is a clear understanding of "Preshipment Cable Test Specimen" location, CMM data and the "Cable Map".

5.6 Marking/Requirements: Spools and exterior packaging shall be identified with the following information in the order shown:

"Superconductor Cable for RHIC Magnets With
8cm Aperture"
Specification No. RHIC-MAG-M-4141, Rev. No. D
BNL Dwg. No. 12000001
BNL P.O. No. ____________
Cable No. ______________
Length ___________ feet
Gross Weight _________ pounds
Net Weight ___________ pounds
Tare Weight ___________ pounds
Cable Machine No. ____________
Cable Measuring Machine No. ______
Date of Manufacture _________
Name of Manufacturer _________

Marking labels shall be applied so they are visible on each spool flange and on the top surface.

5.7 Wire and Cable Identification Numbers: The system for wire and cable identification will be given by BNL to the vendor.



CABLE SPOOLING DIRECTION

Fig.1

APPENDIX A
FREQUENCY OF SAMPLE TESTING

I. Wire Testing

A. Reference: Table I. Wire Dimensional and Mechanical Requirements. All measurements to be completed by the vendor.

Requirement	Test Frequency
Nominal Filament Diameter and Spacing	Demonstration from billet design
Number of Filaments	Vendor QC
Wire Diameter	Continuous laser micrometer measurements
Wire Twist Direction and Pitch	Vendor QC
Wire Sharp Bend Test	Min. four samples from each prod. unit or 25%, whichever greater
Wire Springback Test	Vendor QC
Wire Surface Condition	Vendor QC
Wire Minimum Length	Vendor QC

APPENDIX A (Cont'd)

I. Wire Testing (continued)

B. Reference: Table II. Wire Electrical Requirements.
All measurements to be completed by the vendor.

Note: A wire test specimen shall be delivered to BNL which is adjacent to the location used for each vendor wire electrical test. Also see paragraph 4.5

Requirement	Test Frequency
Wire Critical Current at 5.0T - to satisfy minimum and variation requirements	Min. four samples from each prod. unit or 25%, whichever greater
Wire Maximum Critical Current at 3.0T	Min. four samples from each prod. unit or 25%, whichever greater
Wire Maximum R(295)	Min. four samples from each prod. unit or 25%, which ever greater
Wire Minimum RRR	Min. four samples from each prod. unit or 25%, whichever greater

Definitions for Wire Testing:

1) A "spool" consists of a continuous (unbroken) length of wire.

2) A "production unit" consists of wire from a common multifilament billet, which goes through identical mechanical and thermal processing.

3) Where a specified number of samples are to be tested from a "production unit", these specimens must be selected from widely separated portions of the "production unit".

4) "Vendor QC" indicates that the Quality Control (QC) of the parameter is the responsibility of the vendor. The vendor must initiate a program to assure control of the parameter within the required tolerance.

5) In order to assure confidence in results from wire sample measurements, in case there is a large number of "spools", it is necessary to require a minimum of four (4) samples be tested from each "production" unit or 25% of the number of "spools", whichever is greater.

APPENDIX A (Cont'd)

II. Cable Testing

A. Reference: Table III. Cable Dimensional and Mechanical Requirements. All measurements are to be completed by the vendor with the exception of Cable Keystone Angle with separate off-line tooling; see paragraph 3.2.5.4.

Note: The Preshipment Cable Test Specimen which is delivered to BNL shall be adjacent to the location used by the vendor to verify the cable dimensional and mechanical requirements by off-line measurement.

Requirement	Test Frequency
Cable Mid-Thickness, Width and Keystone Angle	Continuous measurement with CMM, max. interval 100 ft. Check of mid-thickness with separate off-line tooling every continuous length or min. every 15,000 ft.
Cable Lay Direction and Pitch	Vendor QC
Wire Twist Pitch in Cable	Vendor QC
Cable Residual Twist	Every continuous length or min. every 15,000 ft.
Cable Bend Test	Every continuous length or min. every 15,000 ft.
Cable Filament Condition	Every continuous length or min. every 15,000 ft.
Cable Surface Condition	Vendor QC
Cable Lengths	Vendor QC

APPENDIX A (Cont'd)

II. Cable Testing (continued)

B. Reference: Table IV. Cable Electrical Requirements.
All measurements to be completed by BNL using the Preshipment Cable Test Specimen.

Requirement	Test Frequency
Cable Critical Current at 5.0T - to satisfy minimum and variation requirements; Cable Maximum R(295); Cable Minimum RRR	Every continuous length or min. every 15,000 ft.

Definitions for Cable Testing:

- "Vendor QC" indicates that the Quality Control (QC) of the parameter is the responsibility of the vendor. The vendor must initiate a program to assure control of the parameter within the required tolerance.

APPENDIX B
SUPERCONDUCTOR WIRE AND CABLE TEST METHODS

Test Method 4141-1 Wire Sharp Bend Test

Test Method 4141-2 Wire Springback Test

Test Method 4141-3 Verification of Electrical Properties of Superconducting Wire

A. Wire Critical Current Determination

B. Wire R(295) and RRR Determination

Test Method 4141-4 Verification of Electrical Properties of Superconducting Cable

A. Cable Critical Current Determination

B. Cable R(295) and RRR Determination

Test Method 4141-1 - Wire Sharp Bend Test

1. Purpose:

   The purpose of this test is to approximately simulate the deformation to the superconductor wire that may occur during cabling. The sharp bend fixture is made to produce 20% deformation for the wire diameter used.

2. Materials Required:

   A 3-inch long sample of wire to be tested

3. Test Equipment:

   Wire Sharp Bend Test Fixture or equivalent.

4. Applicable Documents:

   None

5. Test Procedure:

5.1 Bend the wire sample in half and place the bend in the slot of the fixture.

5.2 Slide the mating top of the fixture in the slot and squeeze the sample halves together with a bench vise until closed.

5.3 Remove the top of the fixture and loosen the side screw.

5.4 The sample now resembles a hairpin. Examine the bend under 10x magnification to determine if the wire is cracked or deformed. Any indication of cracking or unusual deformation is cause for rejection and must be brought to the attention of BNL.

5.5 Etch the sharp bend sample while stress-free in nitric acid. Use all precautions in handling acids. Examine the sample again with 10x magnification to determine possible filament damage. Any indication of filament damage is cause for rejection and must be brought to the attention of BNL.

Test Method No. 4141-2 - Wire Springback Test

1. Purpose:

   This test establishes a standardized method for testing superconductor wire to determine its springback acceptability for cabling.

2. Materials Required:

   A 3-1/2 ft. length of superconductor wire to be tested.
   Note: Do not bend wire unnecessarily.

3. Test Equipment:

3.1 Springback Test Fixture or equivalent (Fig. 4141-2 #1).
See BNL Dwg. No. 25-718.01-3. This fixture is mounted on a horizontal surface.

3.2 (5.0 $\pm$ 0.2) pound weight.

4. Applicable Documents:

   None.

5. Test Procedure:

5.1 Prepare one end of wire sample with a 1/2 inch long, right-angle bend and tie the other end securely to a 5-pound weight.

5.2 Test the springback fixture to be sure it turns freely.

5.3 Thread the right-angle bend through the test fixture and place in the hole in the spring winder with the locking pin in place.

5.4 Tighten the wire.

5.5 Make sure the right-angle bend is not affecting the "0" reading and the wire is tangent to the spring winding shaft.

5.6 Set "0" on the degree wheel.

5.7 Hang the 5-pound weight over the end of the table. Release the clamp. Hold the spring winder handle and pull the locking pin.

5.8 Wind 10 complete turns and replace locking pin. Then tighten wire clamp.

5.9 Hold spring handle and remove locking pin. Gently let the spring unwind and note the number of revolutions.

5.10 Once the spring has stopped, gently touch the spring handle to make sure the spring has equalized and reached its full springback. Do not unwind the spring.

5.11 Note and record the total number of degrees of springback.

5.12 Cut the sample at the wire clamp and the right-angle bend.

5.13 Carefully slide the spring winder out of its bearings and remove the sample.

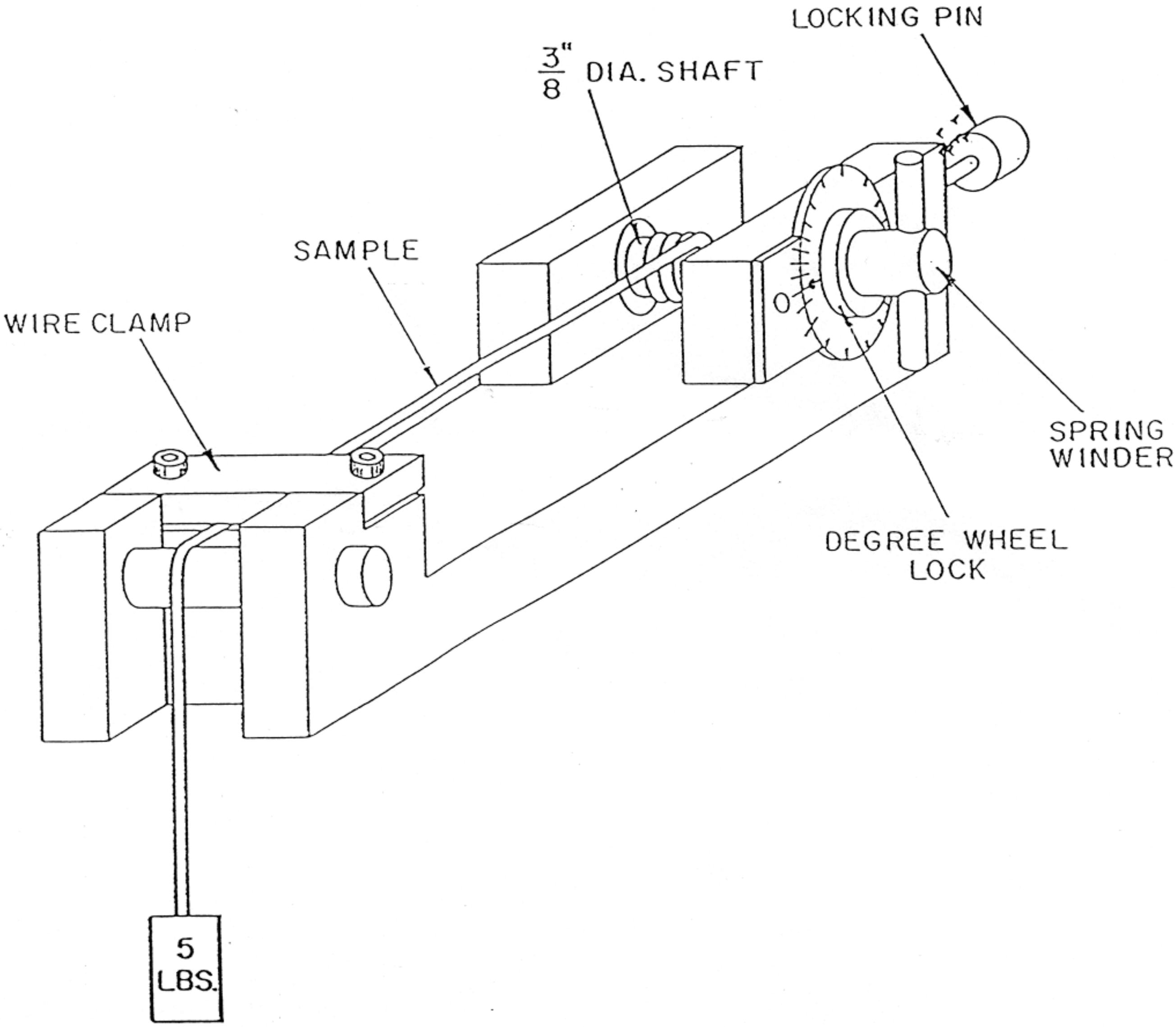


FIG. 4141-2 #1 Spring-back Test Fixture.

Test Method 4141-3 - Verification of Electrical Properties of Superconducting Wire

A. Wire Critical Current Determination

1. General Outline: Definition of Critical Current

The V-I curve is determined as a function of increasing current until an irreversible transition or quench occurs. This measurement is normally carried out in the specified external field at 5.0T applied normal to the wire axis, and in a temperature bath of liquid helium at 4.2K. No correction is made for self-field effects. For currents less than the quench current the V-I curve is reversible.

The critical current, I_c, is defined as that at which the resistance per unit length, R, is:

$$R = 10^{-14} / (\pi d^2/4), \text{ ohms/m}$$

where d is the wire diameter in meters. The effective resistivity of the wire is 10^{-14} ohm ● m at the critical current.

2. Sample Testing

The vendor shall measure the critical current for samples of wire at the specified field value and T = 4.2K. If a temperature of 4.2K is inconvenient, measurements may be made at another temperature and a conversion formula must be supplied. The conversion formula must be approved by BNL. [The notation used here for temperature is as follows: t-in degrees Celsius, T-in degrees Kelvin.]

3. Sample Mounting

The sample wire is most conveniently mounted on a cylindrical grooved form which is made of an insulator, such as G-10, and which fits in a solenoid magnet. (See Section 4 below). The monofilar arrangement, Fig. 4141-3 #1, is used; this lends itself to multiple sample mounting if desired. Voltage taps are arranged as in Fig. 4141-3 #1. Means must be provided for constraint of mechanical motion without interfering with coolant contact: use of a G-10 former with grooved location of wire and careful tensioning during mounting. Care must be taken to ensure that a temperature gradient is not introduced into the region of measurement (gauge length). Care must also be taken in bending the samples, especially at the end of a bifilar sample.

4. Procedure (See Fig. 4141-3 #2)

The sample length (between voltage taps) should be > 25 cm. This corresponds, typically, to a voltage drop of several microvolts at I_c. This is readily measured with the aid of a suitable preamplifier or digital voltmeter. Samples of shorter length may be used if a well functioning nanovolt detection system is available. Equipment must be capable of determining the effective resistivity to a precision of 10%.

The voltage signal should be recorded on an X-Y recorder, preferably in a digital memory device. The V-I curve may be taken either point-by-point (current constant for each measurement) or continuously if induced signals due to ramping are not too large or noisy. When the V-I curve is determined by the latter procedure, care must be taken to ensure that there is no rate effect for the ramp rate used. Typically, current is supplied by a stable, well-filtered power supply. The current should be measured to a precision of ± 0.5%. Use of a low resistance normal metal shunt connected across the sample is permitted provided the resulting correction for shunt current is accurately known and is <0.1%. Electronic circuitry for quench protection is preferable.

It is highly desirable that the Quality Index (n) be estimated using the equation $V = \text{constant} \bullet I^{n+1}$. Data points corresponding to ρ-values less than 10^{-14} ohm•m will usually be less accurate than those for which ρ is greater than this value. Above 10^{-13} ohm•m resistive heating may cause the observed voltage values to be too large. Hence, in fitting a straight line to the log-log plot of the data, the region corresponding to $10^{-14} \leq \rho \leq 10^{13}$ ohm• m should be emphasized.

5. Magnetic Field

The external field is most conveniently applied by means of a superconducting solenoid. The field must be uniform over the sample reference length to ± 0.5%. The direction between field and wire axis must be $90^o \pm 6^o$ everywhere. This range of angles corresponds to an estimated variation in I_c of <0.5%.

6. Temperature Bath Correction

The specification temperature is 4.2K, that of boiling helium at standard atmospheric pressure. The bath temperature must be recorded with the aid of appropriate thermometry (cryogenic thermometer or vapor pressure of bath) with a precision of ± 0.010K (10mK). Deviations of 25mK or less from 4.2K correspond to an error in I_c of 1% or less and may be ignored. For larger temperature excursions the "linear T" type of correction should be applied:

$$\frac{I_c}{I_t} = \frac{T_c - 4.2}{T_c - T}$$

where T_c is the transition temperature at the specified magnetic field. (T_c = 7.2K at 5T.) I_t is the current measured at temperature T, and I_c is the critical current at the specification temperature.

B. Wire R(295) and RRR Determination

1. General Outline: Definition of Residual Resistance Ratio

This method covers the measurement of electrical resistance of Nb-Ti multifilamentary composite wire which is used to make high current superconducting cables. The composite matrix is copper. The resistance per meter is determined at room temperature (295K) and just above the superconductor transition temperature ($T_c \sim 9.5$K). These quantities are designated R(295) and R(10), respectively, and are measured with an accuracy of 0.5%. The ratio R(295)/R(10) is defined to be the residual resistance ratio, RRR.

R(295) is determined chiefly by the copper matrix. For a given wire diameter it provides a measure of the copper-to-non-copper volume ratio.

R(10) is determined chiefly by the residual resistance of the copper matrix and R(295). The ratio RRR provides a measure of the electronic purity of the copper matrix.

2. Apparatus Description

A four-wire method is used to determine the resistance. The wire sample is mounted on a probe which is also used for superconducting critical current measurements. It has leads which are suitable for carrying the required current from room temperature into a liquid helium bath, and potential leads for measuring the voltage drop across a measured length of the test specimen. The probe should be mounted so that the test specimen can conveniently be raised and lowered through the level of a helium bath.

Voltage drops are measured with a voltmeter of 0.5 µV resolution. It is helpful during the low temperature measurement to use an X-Y recorder simultaneously with the digital voltmeter, with Y set to voltage and X to time. (See Section 4 below.)

Currents in the range 0.1 to 1.0A for the R(295) determination and 1 to 10A for the R(10) determination are provided by a well regulated and filtered DC power supply. The current is measured by means of a shunt of 0.25% accuracy.

A thermometer of sensitivity 0.1^{o}C is conveniently used for this purpose as an uncertainty of 1^{o}C is not accurate enough to determine the copper-to-superconductor ratio to ± 0.01.

3. Sample Mounting

The test specimen is wound on a grooved form. The ends are soldered to the copper terminations of the current leads over a minimum length of 1 inch. Voltage taps are soldered to the specimen at a distance of a least 1 inch from the current joint. Voltage taps are soldered to the specimen at a separation distance of at least 1 inch from each current lead connection. It is advisable that these taps be in the form of fixed pins so that the test length be constant throughout a series of measurements. In order to assure an accuracy of 0.2% in length this length should be ~ 25 cm or more. The voltage leads should follow the sample in a non-inductive fashion so as to minimize noise pickup. Alternatively, the sample may be wound non-inductively on the form.

4. Procedure

Room temperature measurements are made at currents which are a compromise between the requirements of sensitivity and negligible ohmic heating. A typical value is 0.5A. Voltage readings are taken for forward and reversed current and averaged.

Low temperature measurements are made in a helium dewar. The probe is raised so that the lowest point of the specimen is a few centimeters above the liquid helium bath level while measuring current is flowing. After a time of order one second the sample warms above T_c(~ 9.5K) and the voltmeter reading suddenly jumps from zero to a finite value corresponding to the sample's normal state resistance. The latter is substantially independent of temperature from the transition temperature, T_c, to 15K (residual resistance region), so that the voltage remains constant long enough to be read. When the X-Y recorder is used, a series of abrupt voltage changes are recorded as the specimen is alternately raised and lowered through the helium bath level. The height of these steps should be reproducible.

5. Room Temperature Correction

If the measurements are made at room temperature the differences from 295K necessitate a temperature correction. Designating the observed resistance as R and the ambient temperature as t(^{o}C), the resistance at the reference temperature of 295K is calculated as follows:

$$R(295) = R/[1 + 0.0039\ (t - 22)]$$

The effect of the Nb-Ti is negligible for the purpose of this correction.

6. Cu/SC Ratio Calculation

The copper: superconductor volume ratio (x) is calculated from R(295) and RRR by means of the formula

$$x = \frac{1 - R(295)\, A/\, \rho_s}{R(295)\, A/\, \rho_{Cu} - 1}$$

where R(295) = resistance of the cable at 295K in ohms/m

ρ_{Cu} = resistivity of the copper at 295K, in ohm ● m

$$= \rho_i \frac{RRR}{RRR - 1}$$

ρ_i = resistivity of pure copper at 295K

$= 1.695 \times 10^{-8}$ ohm ● m

ρ_s = resistivity of Nb-Ti at 295K

$= 60 \times 10^{-8}$ ohm ● m

and A = wire cross section area in m^2

$= \pi d^2/4$ (d = wire diameter in m)

Reference: "Normal State Resistance and Low Temperature Magnetoresistance of Superconducting Cables for Accelerator Magnets" by W.B. Sampson, M. Garber and A.K. Ghosh, IEEE Trans. on Mag. 25, 2097-2100 (1989).

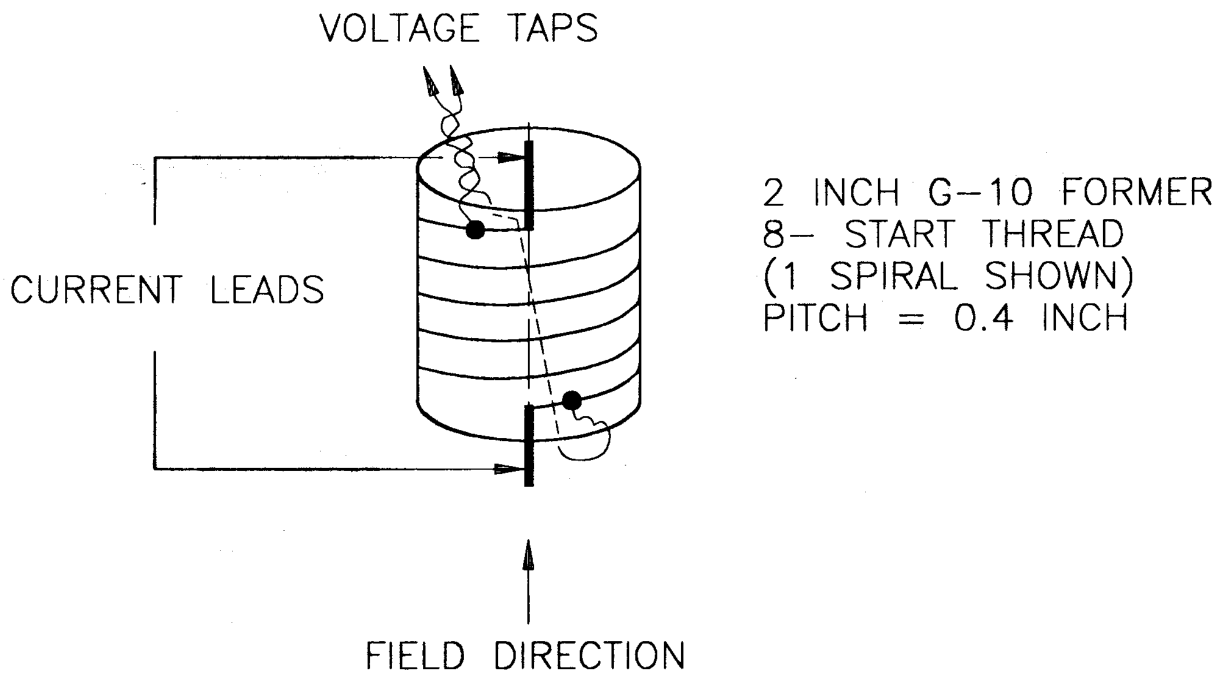


FIG. 4141-3 #1 SAMPLE MOUNTING ARRANGEMENT

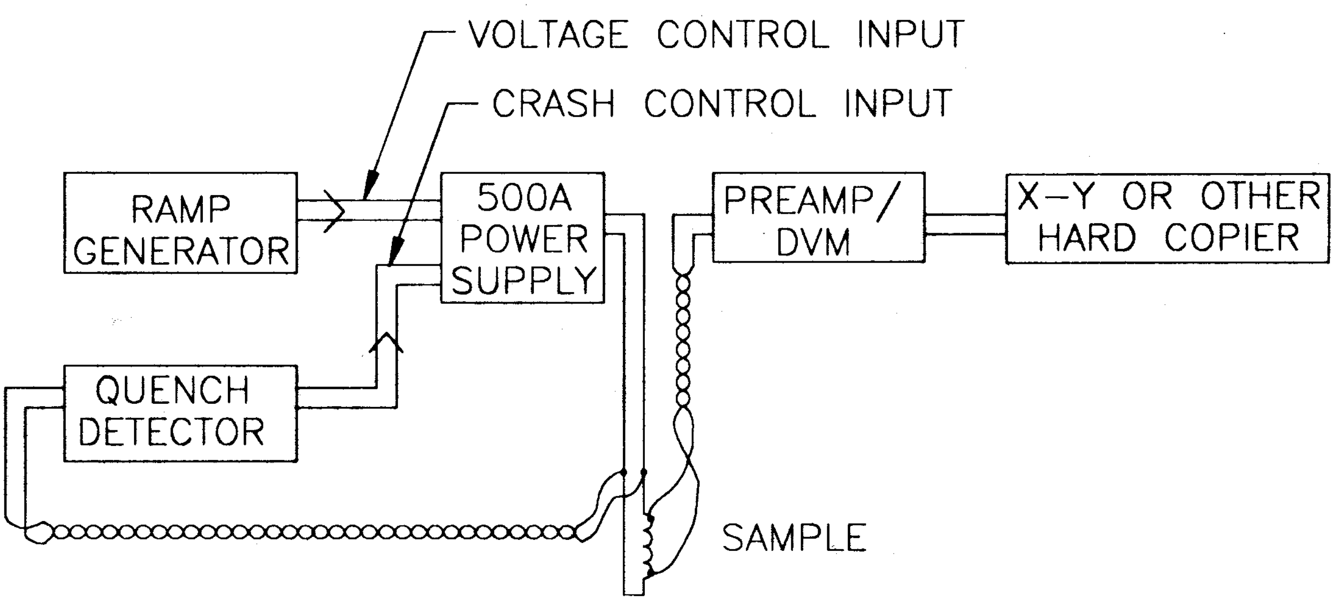


FIG. 4141-3 #2

SCHEMATIC OF ELECTRICAL MEASUREMENT APPARATUS

SK/S00336BS

Test Method 4141-4 - Verification of Electrical Properties of Superconducting Cable

A. Cable Critical Current Determination

1. Introduction

The sections which follow describe the test method used at BNL to determine transport critical currents of cable short samples. The measurement of critical currents of order 10^4 A is more difficult than the corresponding measurement for a wire carrying several hundred amps for a number of reasons. Large power supplies are required and sensitive voltage measurements must be made in the presence of much noise. Forces on the samples are large and care is required to restrain mechanical motion. Finally, self-field effects are large and must be carefully corrected. This section describes the methods and procedures which have been developed at BNL over a number of years. These procedures have proven suitable for production testing.

References:

1. "Quality Control Testing of Cables for Accelerator Magnets" by M. Garber and W.B. Sampson, Supercollider 1, Plenum Publishing Corp., NY, NY.

2. "The Effect of Self Field on the Critical Current Determination of Multifilamentary Superconductors" by M. Garber, A.K. Ghosh and W.B. Sampson, IEEE Trans. on Mag. 25, 1940-1944, 1989.

3. "Normal State Resistance and Low Temperature Magnetoresistance of Superconducting Cables for Accelerator Magnets" by W.B. Sampson, M. Garber and A.K. Ghosh, IEEE Trans. on Mag. 25, 2097-2100, 1989.

2. Relation Between Wire and Cable Critical Currents

For a multifilamentary composite wire, the critical current I_{cw}, may be written as

$$I_{cw} = J_c (\pi d^2/4)/(1+x)$$

where J_c = critical current density in superconductor, A/mm^2

d = wire diameter, mm,

x = copper:superconductor volume ratio (or more generally copper:non-copper ratio)

The quantity J_c provides a figure for comparing wires of different diameter or of different copper/superconductor ratios. (The intrinsic current density of the Nb-Ti may be larger than J_c since the latter is reduced somewhat by variations in cross-section of the filaments.)

Present manufacturing art is such that we may expect to obtain, in multifilamentary composite wires of diameter 0.1 to 1 mm

$$J_c > 2600 \text{ A/mm}^2 \text{ (T = 4.2K, B = 5T)}$$

This value serves as the basis for a wire specification. [The notation used here for temperature is as follows: t-in degrees Celsius, T-in degrees Kelvin.] For a RHIC wire, for example,

$$d = 0.648 \text{ mm } (= 0.0255 \text{ in.})$$

$$x = 2.25$$

and we may expect

$$I_{cw} > 264 \text{ A} .$$

The critical current of a cable, I_c, is somewhat less than the sum of the individual wire values as there is invariably some degradation during the fabrication of the cable. This is expressed as follows:

$$D = 1 - (I_c/\Sigma\, I_{cw})$$

An allowance for degradation, in modern practice, is $D < 0.05$ (=5%). If we let $\Sigma\, I_{cw} = N \bullet 264$ A where N = number of wires in a RHIC cable = 30, then

$$I_c > 0.95 \bullet 30 \bullet 264 \text{ A}$$

$$= 7524 \text{ A (at 4.2K, 5.0T)}$$

The critical current is a function of temperature, T, and magnetic field, B. It is generally necessary to convert (or "correct") short sample test results obtained at particular values of T and B, to values corresponding to a standard temperature and field. The steps in this conversion are as follows:

a) Obtain raw data for several applied fields: I_t, critical current at bath temperature,T, and applied field, B_a.

b) Convert I_t to I_c, the value corresponding to reference temperature T_{ref}.

c) Calculate the peak field, B: the sum of the applied field and the self field, due to the measurement current.

d) Plot I_c vs. B and calculate I_c at the reference field from a linear fit to the data.

The calculations used in the above steps are described in detail below. The I_c vs. B short sample curve may be combined with the load line of the magnet to obtain a prediction of its expected performance.

2. Definition of Critical Current

Accelerator magnet cables are designed to carry currents of 1-10 kA in fields of order 6T, at 4.2K. The voltage drop under these conditions is not zero; typically it is a few microvolts per meter. The variation of voltage with current can be measured in a range corresponding to about 0.5 µV/m to 50 µV/m. Smaller voltages are difficult to measure. At the high end, the V-I curve is unstable and an ineversible quench occurs. For currents less than the quench current, the V-I curve is reversible. The critical current is a property of the reversible portion of the V-I curve. It is defined as that current for which

$$V/I = 10^{-14}/(N\pi d^2/4)$$

where

V = voltage drop per m
I = current in amps
N = no. of wires in cable
d = wire diameter in m

For purposes of numerical illustration let d = 6.48×10^{-4} m (=0.0255 in.), N = 30, and I = 7000 A; then V = 7.1 µV/m. It is desirable, therefore, that test lengths of order 1 m be used when the measuring sensitivity is of order 0.1 µV.

The shape of the V-I curve is of the form

$$V = \text{constant} \bullet I^{n+1}$$

where $\rho = (V/I(N\pi d^2/4)$. The quantity n is routinely measured as described in Section 6 below. Large n-values are indicative of uniform filaments. The n-value is, therefore, a useful diagnostic for monolithic conductors and individual wires, although less so for cables. It is sometimes required that n exceed a specified value for some types of conductor.

The quench current is dependent on T and B in a somewhat similar way as the critical current. Unlike the critical current, however, it is also dependent on several external factors: insulation, ramp rate, mechanical security. These affect the characteristic feature of quench current behavior, viz., training. This is the increase in quench current upon successive applications of current until, except in pathological cases, a limiting or plateau value is reached. This value is referred to as I_q. Temperature and field corrections are not generally made for I_q. The number of training quenches is minimized in short sample testing by using bare cable samples and by strong mechanical clamping as discussed below.

I_q is generally greater than I_t and, as it provides a measure of the ultimate current carrying capability of the cable, it is routinely recorded. If I_q is less than I_t, the latter may be determined by extrapolation provided there is enough of the V-I curve to permit this. However, in this event I_t is of academic interest only as it cannot be attained in practice.

3. Magnet; Temperature Bath; Power Supplies

The sample probe is located in a dipole magnet which is 48 in. long and has a 3-inch diameter bore. The maximum field is 6T at a current of approximately 3 kA. The sample test length is 70 cm; over this length, the field homogenity is about 1/1000. The magnet is equipped with a superconducting persistent switch which is very useful for keeping the field constant in time and noise free.

The magnet is supported in a vertical dewar of 24 in. ID and length 9 ft. Current is supplied to the samples through 15000 A gas-cooled leads and to the magnet through 5000 A leads. A dewar overpressure of 2-3 psi provides the gas flow for these leads.

A 4 kA power supply is used to energize the dipole magnet. A 15 kA power supply is used to supply the sample current. Although peak-to-peak AC noise is not small (it is of order 1 mV), this does not affect the critical current determination because of the method of measurement described below.

4. Sample Mounting

The samples are mounted in a compression fixture which is illustrated in Fig. 4141-4 #1. The usual test arrangement involves four bare cable samples. As these are keystoned, (i.e., they are trapezoidal in cross-section), care is taken to alternate thick and thin edges so that pairs of conductors present parallel surfaces to the clamping faces. As indicated in Fig. 4141-4 #1 there are a series of separators: 0.030 in. thick G-10 strips which carry electrical instrumentation described below, and 0.010 in. thick Mylar strips which insulate adjacent samples of the upper and lower cable pairs.

Compression is applied by tightening 3/8 in. bolts. These run along each side at 1-1/2 in. intervals. A torque of 200 inch-pounds is used to tighten the bolts. This produces a clamping pressure of 10 $\pm$ 1 kpsi at room temperature. The pressure has been found to increase slightly at low temperature. With this method training behavior is limited to a few quenches.

The sample compression fixture is supported together with the sample leads from a room temperature flange, which may be rotated. The standard configuration for quality control testing is the perpendicular one, i.e., the applied dipole field is perpendicular to the sample faces. In this configuration, a strong twist about a vertical axis is generated by a bifilar sample for currents above a few kiloamps in fields above several Tesla. Rotation of the sample fixture relative to the magnet is prevented by means of a locating key on the fixture and a slotted plate on the magnet.

Figure 4141-4 #2 shows schematically how the cables are connected to each other and to the gas cooled leads. The connections are made using ordinary soft solder over a 1-1/2 in. length. A typical joint resistance is about 10^{-9} ohm. The samples are excited in pairs, either A-B, or C-D.

5. Electrical Instrumentation

Primary instrumentation consists of the following:

- Five voltage taps and thin foil heater element for each sample. These are contained on the G-10 strips shown in Fig. 4141-4 #1. The voltage taps work by the pressure contact of a copper wire across the width of the sample; the leads run out through a fine groove in the G-10. The heater element is a strip of stainless steel foil, 0.0005 in. thick x 1/8 in. x 1/4 in.,which is located in a shallow well formed in the G-10 strip.

- Hazemeyer or other manufacturer DCCT secondary current standard.

- Digital voltmeters, 6-1/2 digit, 0.1 μV sensitivity.
- Nicolet 12 bit, 4 channel digital oscilloscope.
- Two calibrated carbon resistor thermometers, located at each end of the magnet.
- Isolation preamplifiers, 1 μV noise level.

Secondary instrumentation consists of the following:

- Quench current protection circuits for the magnet, the gas-cooled leads, and the samples.
- DC power supplies for persistent switch, and sample heater element.
- Pulse power supply for sample heater element.

6. Measurement Procedure

The cable samples are energized in pairs, either A-B or C-D in Fig. 4141-4 #2, and the V-I curves are determined simultaneously for each member of the bifilar pair. In the event that one member has a low I_q its partner may be unmeasurable in the set-up. The latter must be tested at another time with a partner having a comparable I_q - another piece of the same cable, for example. In situations like the preceeding, a minimum of two and perhaps three of the cable samples can be measured. In quality control tests of production cables, the match between samples is close enough that I_c's can usually be determined for all four samples. In the rest of this section we shall describe the procedure for testing one cable only, it being understood that a pair of samples, or all four, are under simultaneous test.

The measurements are made with the helium bath level above the upper sample and well above the top of the dipole magnet. The magnet field is set to a desired value and locked in with the persistent switch. The standard arrangement is such that the field is oriented perpendicular to the cable face.

The relative direction of the current flow and of the magnet field is very important for reasons which will be discussed below. The polarity of the power supply connections is carefully checked, therefore. Before the V-I curve is measured the sample is trained. This is done by ramping the current until a quench occurs. For relatively high Cu/SC ratio cables, as in the RHIC design, one quench is usually sufficient to reach the plateau value of I_q.

The V-I curve of the sample is now determined. A point-by-point method is used: the current is ramped to a suitable value, stopped, and the voltage measured. This is repeated for progressively higher values of current until a quench occurs (usually while ramping between currents). The most important feature of this method is that a very high degree of filtering of noise voltage can be achieved by the following technique. The noise is mostly in the form of harmonics of the line frequency. By integrating the voltage signal for an integer number of cycles, this harmonic noise is filtered to a very low value. In practice, the integration is over 100 cycles, and AC peak-to-peak voltages of order 10^{-3} volts are reduced to an effective uncertainty in any DC reading of 10^{-7} volts. Another advantage of the point-by-point method is that inductive voltage drops are eliminated. A third feature is that the measurement is a DC measurement - there is no ramp rate effect in the I_t determination. I_q is determined while ramping by means of a peak-reading DVM. The ramp rate is about 200 A/sec (between points). I_q is determined by one sample of the pair being measured; this value is a lower limit of I_q for the other sample. By observing the quench on a digital oscilloscope one can determine in which sample the quench originates. It is usually the one with the lower I_t value.

A few points are taken in the first several kiloamps of current, where the DC voltage is below the limit of detectability. This establishes a zero level base-line. Once the voltage signal exceeds a few tenths of a microvolt, the interval between measurement currents is reduced. Between the onset of a detectable voltage drop and the quench, 10 or 15 points are taken, typically.

The digital voltmeters are under computer control, and the set of V-I data is now promptly analyzed by a technician, utilizing the same on-line program which was used to take the data. The V-I data are converted to log ρ - log I data and fitted by a straight line. This gives the 10^{-14} ohm ● m current and the n-value (the slope of the log-log plot). Also see the comments included in Test Method 4141-3, Section A-4. The following data are the result of the measurement: B_a, T, I_t, I_q, n, where B_a is the applied field, and I_q is the quench current or a lower limit of it. This procedure is repeated for each of the four cables at several fields in the vicinity of the specification field.

The temperature sensors are monitored continuously. If the temperature varies more than ± 0.010K during the taking of a V-I curve, the measurement is aborted. Efforts are then made to reduce the temperature variation. These include waiting for the helium bath to settle down, increasing the flow of gas through the current leads, and refilling the dewar. The last measure is generally unnecessary if the run is less than 3 hours. (The usual run duration is 2 hours.)

7. <u>Temperature Calculation</u>

The discussion in this section pertains to Nb-Ti conductors of composition and metallurgical treatment appropriate for accelerator magnet applications.

Calculations of the critical currents at temperatures other than that at which I_t is measured are made using a linear fit:

$$\frac{I_c}{I_t} = \frac{T_{ref} - T_c(B)}{T - T_c(B)}$$

where I_t is the measured critical current at T and I_c is the calculated critical corresponding to T_{ref}. $T_c(B)$ is an effective critical temperature, i.e., the temperature at which the linear portion of the I_c vs. T curve for Nb-Ti extrapolates to zero. The above equation is a good approximation in the temperature range of interest, viz., 2K to 4.6K. A good approximation for $T_c(B)$ in the field range of interest, viz., 3T to 8T, is given by the following expression:

$$T_c(B) = 9.2\left[1 - \frac{B}{14.5}\right]^{0.59}$$

where B is the field in Tesla. B is determined as described in the following section.

8. Magnetic Field Correction (See Reference 2)

The magnetic field is the sum of the applied field produced by the dipole magnet and the self-field produced by the measuring current. The latter produces a substantial correction. However, its effect is difficult to assess precisely because it is spacially non-uniform, and therefore to calculate exactly, and because it depends upon the geometrical details of the bifilar sample. Experience has shown that the following assumptions give results which are self-consistent for a wide variety of geometries and which give reliable predictions of magnet behavior.

a) The critical current of the sample is determined by the peak magnetic field. This depends, of course, on the orientation of the applied field and the direction of the sample current. This important point will be discussed further in the next section.

b) The sample current is distributed uniformly over, and normal to, the area of the trapezoid which encloses the cable cross-section.

c) The geometry is accurately reproducible; this is a matter of care in assembly, as discussed above.

With the dipole field perpendicular to the wide face of the sample, the peak field occurs at a point on the surface of the sample where the self-field and the applied field are very nearly parallel; that is, they are simply additive. For the standard test configuration, therefore, the self-field correction can be written:

$$B = B_{peak} = B_a + c\bullet I$$

where B_a = dipole field and c = geometric constant. Below is given the value of c for RHIC cable, for B_a perpendicular to the sample, and for the standard BNL test geometry in which the bifilar samples are separated by 0.010 in.

Self-field constant, c, gauss/amp, for RHIC cable: 0.395.

9. Critical Current of the Thin Edge:

The thin edge of a keystone-shaped cable is of special interest for two reasons. First, it forms the inner surface of a dipole (or quadrupole) magnet coil, and the maximum value of the field occurs there. Second, this part of the cable experiences the most deformation during fabrication, and possibly the most degradation. The bifilar sample test arrangement with applied field perpendicular has the characteristic feature that the peak fields occur at diagonally opposite points, at the two thin edges (c.f. Fig. 4141-4 #3). Experience has shown that when the current is reversed, so that the peak field points are along the thicker edges, a higher critical current is measured (even though the calculated peak field is slightly higher in this case). This is due to the smaller degree of degradation along this edge. In practice, the quality control test determines the critical current for the thin edge; i.e. the field and current direction are oriented as in Fig. 4141-4 #3.

10. Data Averaging Using I-B Graph; Degradation

The critical currents are plotted on a graph of I vs. B and I_c is obtained from an interpolation to the specification field.

The degradation of the cable, as mentioned before,is $D = 1 - (I_c/\Sigma I_{cw})$. In practice, a few wires may be measured and ΣI_{cw} estimated from this sample, but in cases where questions arise as to whether D meets a specification, it is necessary to determine I_{cw} for all the wires in the Cable Map.

We have ignored the fact that the critical current of a wire is also subject to a self-field effect. However, it has become general practice not to take account of this correction, notably in discussions of J_c in the literature. For cables it is not acceptable to ignore self-field corrections for the reasons given previously: sensitivity of measurements to sample configuration and comparison of data with magnet performance. As a result of this convention, the specified degradation is lower than the true degradation, which would take account of wire self-field effect and lead to a larger value of $\Sigma\ I_{cw}$.

B. Cable R(295) and RRR Determination

1. Scope

This method covers the measurement of electrical resistance of cables made from Nb-Ti multifilimentary composite wires. The composite matrix is copper. The resistance is determined at 295K and at a temperature just above the superconducting transition, about 10K. The resistance per unit length at these two temperatures is designated R(295) and R(10), respectively. The residual resistance ratio, RRR, is defined to be R(295)/R(10). R(295) is measured with an accuracy of 0.5%; R(10) is measured with an accuracy of 2%.

2. Purpose

The quantities R(295) and R(10) provide a measure of the amount of copper and its electronic purity. Cu/SC is calculated as discussed in Section 6.

The quantity RRR provides a measure of the state of anneal of the copper matrix. It may be used to check that a cable has been given a post-cabling heat treatment in order to facilitate coil winding, if this has been specified. Such cables have RRR values over 100, whereas unannealed cables have values around 70, typically, if the wire has a final anneal, and 35 if it has not been annealed during the final drawing stages.

3. Apparatus; Test Sample; Procedure

The measurements are made on the samples assembled for critical current measurements, as described in the preceding part of this Appendix.

The room temperature measurement is made using a DC current of 1 A, and voltage contacts 70 cm apart (see Fig. 4141-4 #2). A thermocouple device of 0.1^0C accuracy is used to determine the ambient temperature.

The low temperature measurement is a dynamic one, made by inducing a superconducting-normal state quench while the cable is carrying current. Referring to Fig. 4141-4 #2, a quench is triggered in Cable A, for example, by means of heater HA.

The resulting waveform observed at nearby voltage taps, A2-A3 or A3-A4, consists of three parts: a superconducting state baseline voltage, a linear ramp voltage corresponding to the passage of the superconducting-normal interface between the voltage taps, and a slowly increasing signal characteristic of the normal state resistance. The latter increases in time due to normal state heating. However, at first the voltage is almost constant due to the residual resistance characteristic of the copper. Thus, there is a kink in the voltage waveform at the beginning and at the end of the linear ramp portion. The voltage difference between these two points equals the current times the residual resistance of the section of cable between the voltage taps. The resistance per centimeter is determined for two pairs of taps (A2-A3 and A3-A4 in the above illustration) and averaged. The taps are relatively close to the heater in order to minimize the effect of current fall-off which results from the increase of normal state resistance as the quench propagates.

Some rough values to illustrate the magnitude of the quantities involved are: I = 3000 A, V = 3 mV/4 cm, R = 0.25 μV/cm.

The usual specification is for zero magnetic field. The above measurement may be made in an external field, however, in order to determine the magnetoresistance effect.

4. Room temperature Resistance Correction

Normally occurring room temperature variations produce significant variations in the measured resistance. Designating this resistance as R_m and the ambient temperature as $t(^0C)$, the resistance at the reference temperature of 295K is calculated as follows:

$$R(295) = R_m/[1 + 0.0039\ (t - 22)]$$

The effect of the Nb-Ti is negligible for the purpose of this correction.

5. Reported Quantities

The manufacturer ID, wire diameter, nominal Cu/SC ratio, and number of wires are recorded for each test specimen. The following results are recorded:

R(295) (μ ohms/cm)
R(10) (μ ohms/cm)
RRR

Optional (if requested)

R(10) for B = 5T
RRR for B = 5T

6. Copper/Superconductor Ratio

The copper/superconductor ratio of the cable is determined in nearly the same manner as for the wire; see Test Method 4141-3, Section B-6, "Cu/SC Ratio Calculation". The same formulas are used but with two exceptions:

a) The area is that of all the wires, viz., $N\pi d^2/4$.

b) The spiral path of the wires necessitates applying a length correction to the measured value of R(295). For RHIC cables R(295) is replaced by 1.04 ● R(295) in the formula of Section B-6, Test Method 4141-3.

The specification on R(295) is based on the cited calculations. It is an alternative to the etch and weigh Cu/SC specification and is operationally preferable. The range of acceptable values of R(295) is determined by the Cu/SC ratio and the mean wire diameter. The maximum resistance specification determines the minimum Cu/SC ratio with an accuracy which is determined by the wire dimensional tolerance.

The resistance determination of Cu/SC for cables is routinely done in the BNL short sample test procedure and serves as an accurate check on the wire data. Cable and wire Cu/SC values agree to better than 2% in well-behaved cases, i.e. those in which there have been no errors in the strands used for cabling. This determination is, therefore, an important quality control check.

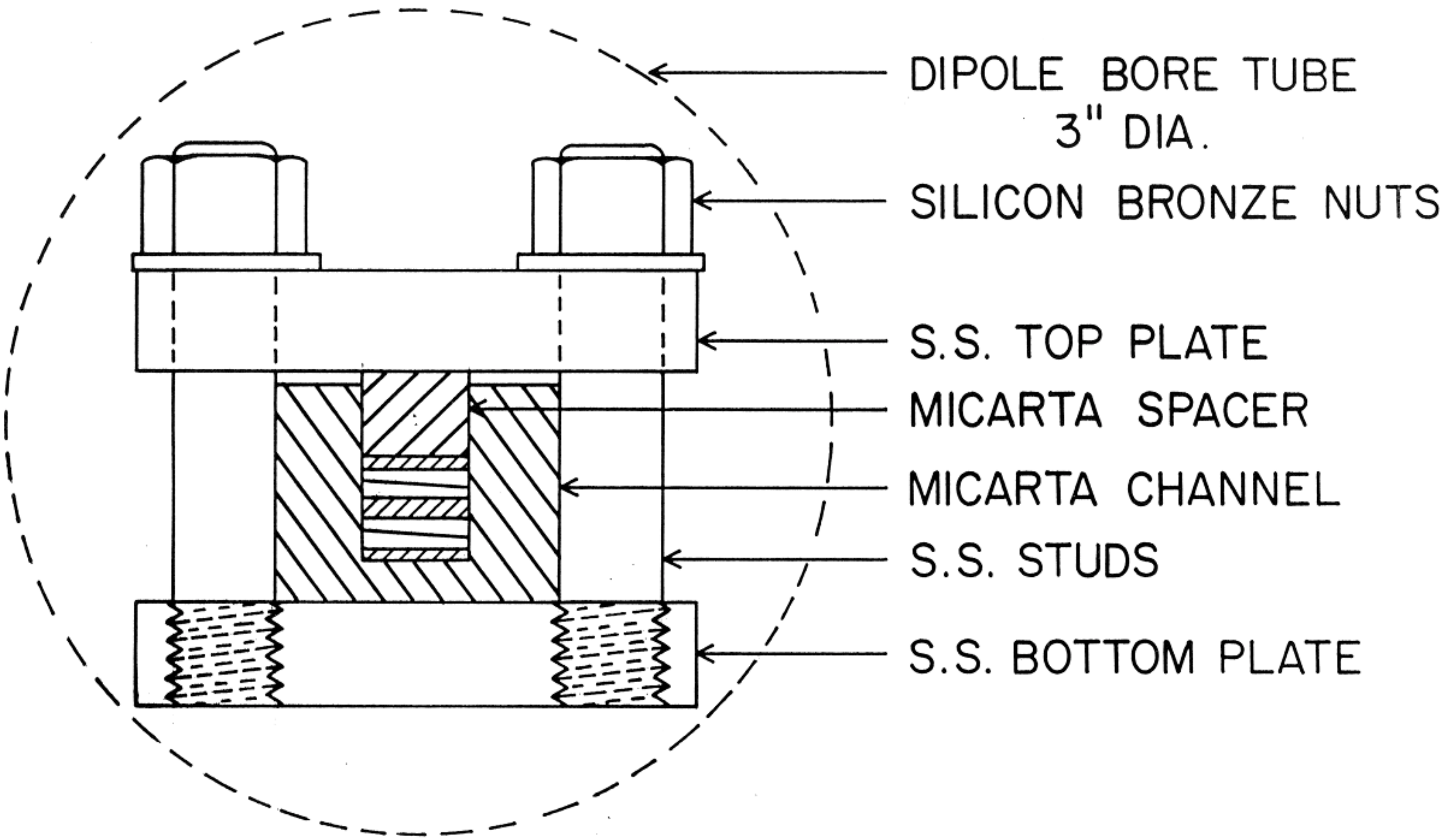


FIG. 4141-4 #1 Mechanical Assembly.

Two bifilar pairs of keystoned samples are assembled, as shown. The members of each pair are separated by Kapton, 0.010 in. thick. Instrumentation is located in G-10 strips placed below, between, and above the bifilar pairs; thicknesses of the G-10 strips are 0.030, 0.100, and 0.030 in., respectively. The stainless steel studs are located 1.5 in. apart along the 48 in. length of the fixture. The silicon bronze nuts are tightened to 200 in.-lbs. torque resulting in a mean pressure on the samples of approximately 10 kpsi.

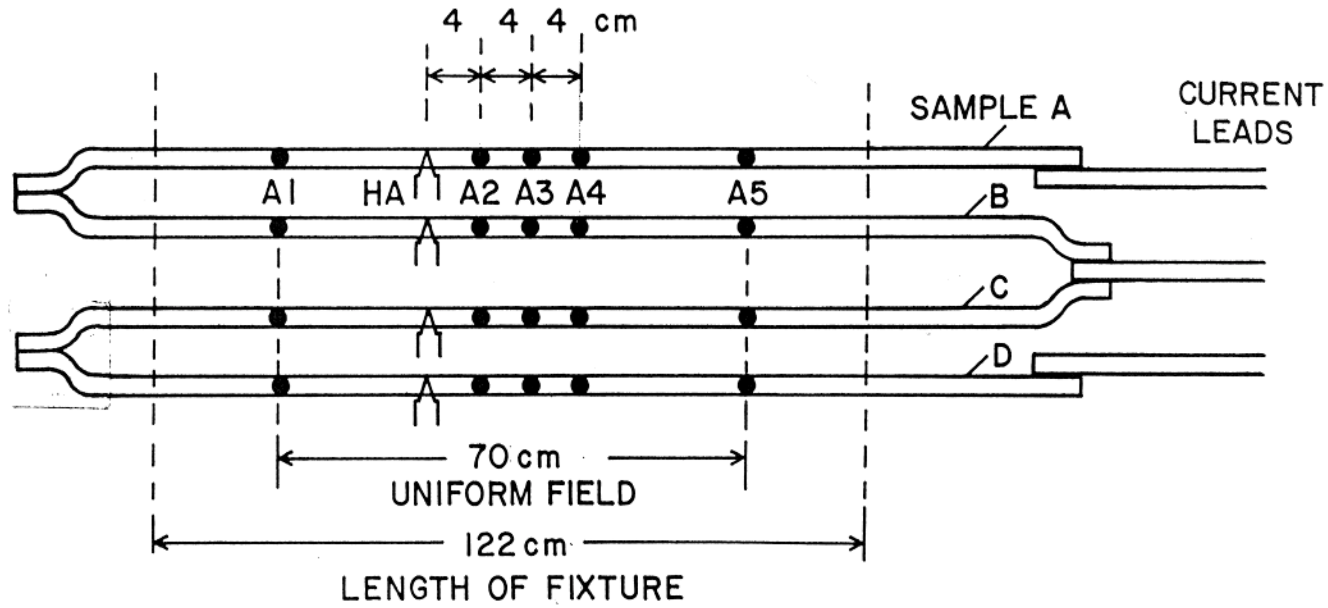


FIG. 4141-4 #2 Electrical Wiring Schematic.

Samples are tested in pairs: A-B and C-D. The critical current and room temperature resistance of sample A, for example, are determined using voltage taps A1 and A5. The low temperature resistance and quench propagation velocity are determined using the spot heater HA and voltage taps A2, A3, and A4.

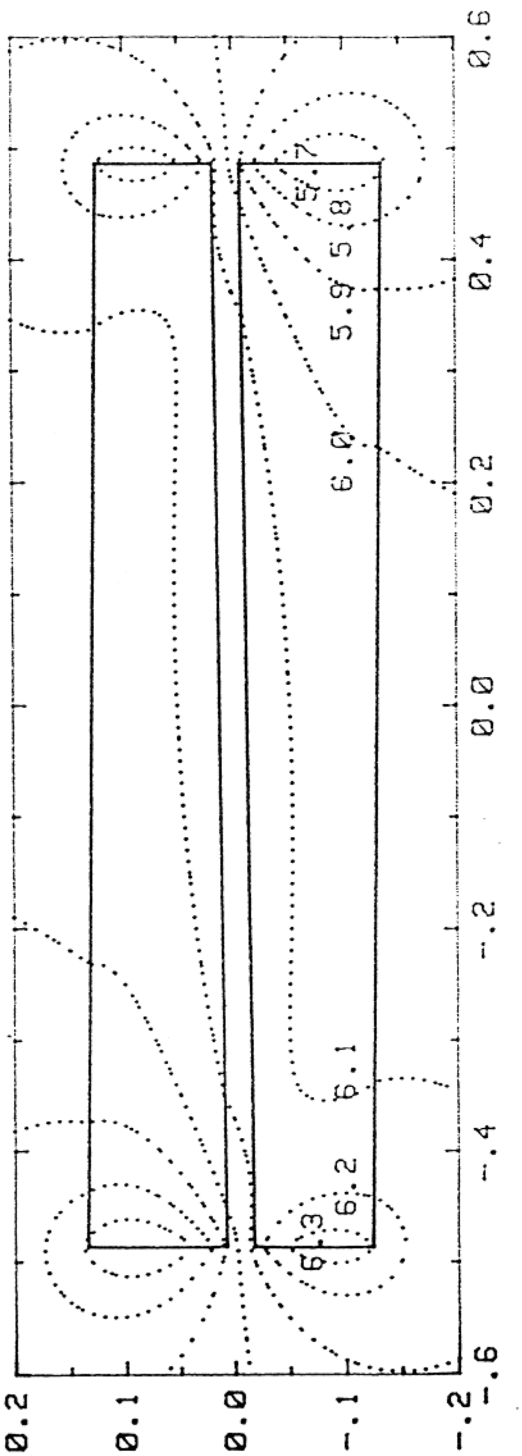


FIG. 4141-4 #3 Contours of Constant Field Magnitude.

Calculated contours for perpendicular applied field of 6 T and current of 10 kA. The peak field is 6.4 T and occurs along the thinner edge of each conductor (left side of lower and right side of upper conductor).

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Quality Control Testing of Cables for Accelerator Magnets

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ABSTRACT

A large number of cables have been tested for the CBA, HERA, and SSC Projects. The short sample test procedures and apparatus are reviewed. A simple rule for estimating cable performance from measurements on strands taken from the cable is described. By using this "rule of thumb" cable vendors can make reliable estimates without having to invest in the substantial equipment required for full cable testing. Extracted strand tests should be checked periodically by full scale tests on complete cables.

INTRODUCTION

Short sample testing of superconducting cables used in accelerator magnets is required in order to ensure that the individual strands have not been unduly degraded during cabling. Occasionally this can be quite large; an example of this is given below. Another factor is the large increase in critical current density which has been achieved in recent years[1], which has made wires with perfectly reproducible properties difficult to manufacture. Mixing and matching of strands is used to produce constancy in cable properties, but this must be verified by short sample testing.

The first large scale program of short sample cable testing was undertaken for the erstwhile ISABELLE-CBA Project about ten years ago.[2] Test methods have been improved continuously since then. The development of cables carrying currents of order 10 kA at 6T, 4.2K, more than double the current of a decade ago, has led to the need for special mounting procedures and careful self field corrections to the measured results. An earlier paper reviewed the important features of the BNL cable test methods.[3]

Further details have been given in several conference papers. As indicated in the following sections, a large investment in equipment and refrigeration is required to test high current superconducting cables.

*Work performed under the auspices of the U.S. Department of Energy.

The straight line in Fig. 1 is drawn with a slope of 7 x 10^{4} ohms. This corresponds to constant resistivity of 10^{-12} ohm cm. The intersection of this line with the V-I curve of the sample is the critical current, I_c. In practice the quantity ρ = VA/Iℓ is plotted vs I on a log-log plot. This curve is usually well approximated by a straight line, and I_c can be read off with good accuracy from the point whose ordinate is 10^{-12} ohm cm. The slope of this line, n, measures the steepness of the superconducting-normal transition, which depends on the uniformity of the NbTi microfilaments. Low n-values generally lead to low I_c's other things being equal.

I_c is often referred to as the "short sample" current in discussions of the performance of magnets made of the given cable. This is because it is a fact of experience that the magnet quench current is usually within a few percent of I_c (either more or less). The correlation is not exact, however, because of such things as variation of I_c along a cable, heating at cable joints in the magnet, variations in heat flow to the cable, etc. In any case, the quench current, I_q, in a short sample test is usually significantly greater than I_c, typically by about 10%. In general, the greater the Cu/SC ratio the greater the ratio of I_q to I_c.

In addition to the field, the temperature of the measurement must be reported. The sample and dipole magnet are placed in a helium bath. High current gas cooled leads necessarily require a bath pressure greater than standard atmospheric. As a result the temperature of measurement is about 0.2K above the normal boiling point of helium. It is desirable to refer measured values to a common reference temperature. This is done by means of the so-called Lubell formula.[7] A reference temperature of 4.22K is frequently chosen, although this is not necessary. The HERA project, for example, specifies 4.6K as reference temperature for short sample data. In order to distinguish between measured critical current values and those referred to some reference temperature we use the following notation: I_t is the critical current as measured at the helium bath temperature, T; I_c is the critical current at the reference temperature.

CABLE CLAMP ASSEMBLY

In order to observe V-I curves like that of Fig. 1, it is necessary to prevent any cable motion which would be generated by the large Lorentz forces which occur at high currents. Figure 2 shows the method by which this is done. A bifilar sample is used (two such are shown in the figure). The thin and thick edges of keystoned cables are placed as shown so that the top and bottom surfaces are parallel and the applied stress is uniform. The net Lorentz force on the assembly is zero. However, the perpendicular field produces forces on the members of the bifilar pair which try to make them slide apart in a shear like fashion. (The perpendicular field is oriented relative to the current direction so that the sum of the applied and self fields is a maximum at the thinner edge of the cable. This produces a tendency to shear apart rather than together. Cf reference 4.) In order to prevent this motion, a large compressive stress is required. The value required varies inversely with Cu/SC ratio. However, in order to standardize the procedure, a value of 10 kpsi is used for all cables. This is adequate for most of the cables commonly tested. Further details on the stress dependent behavior are discussed in reference 6.

Although the separation between cables in the bifilar pair is small, the couple created by the shear forces is enough to produce significant twisting of the assembly unless otherwise prevented. To do this the ends of the assembly are locked in position relative to the magnet bore tube by a key-slot arrangement.

Thus, it is not feasible for each vendor to make these tests. However, a simple correlation exists between the current of strands taken from a cable and the full cable current. By utilizing this "rule of thumb", the vendor can obtain prompt, in-house feedback between the manufacturing process and short sample measurements. Examples are given below which show that a relatively small number of strands need be sampled in order to get a reasonable estimate of cable performance.

CABLE TEST METHOD

The V-I curve of a recently tested SSC cable is shown in Fig. 1. The sample is mounted in a dipole magnet with the field oriented perpendicular to the flat surface of the cable. The sample test length, i.e., that part which is in the uniform field region, is 700 mm long. Each half of the sample can be measured separately if, for example, it is desired to locate suspected flaws. The sample is long enough to provide adequate voltage compared with the DC noise resolution, which is about 0.2 microvolts. This sensitivity is achieved by means of a point by point determination of the V-I curve as follows. The current is incremented in steps. At each value the sample voltage is integrated for a time equal to 100 periods of line voltage, thus filtering power supply noise. The magnet is operated in the persistent mode so essentially no noise is contributed by the dipole field.

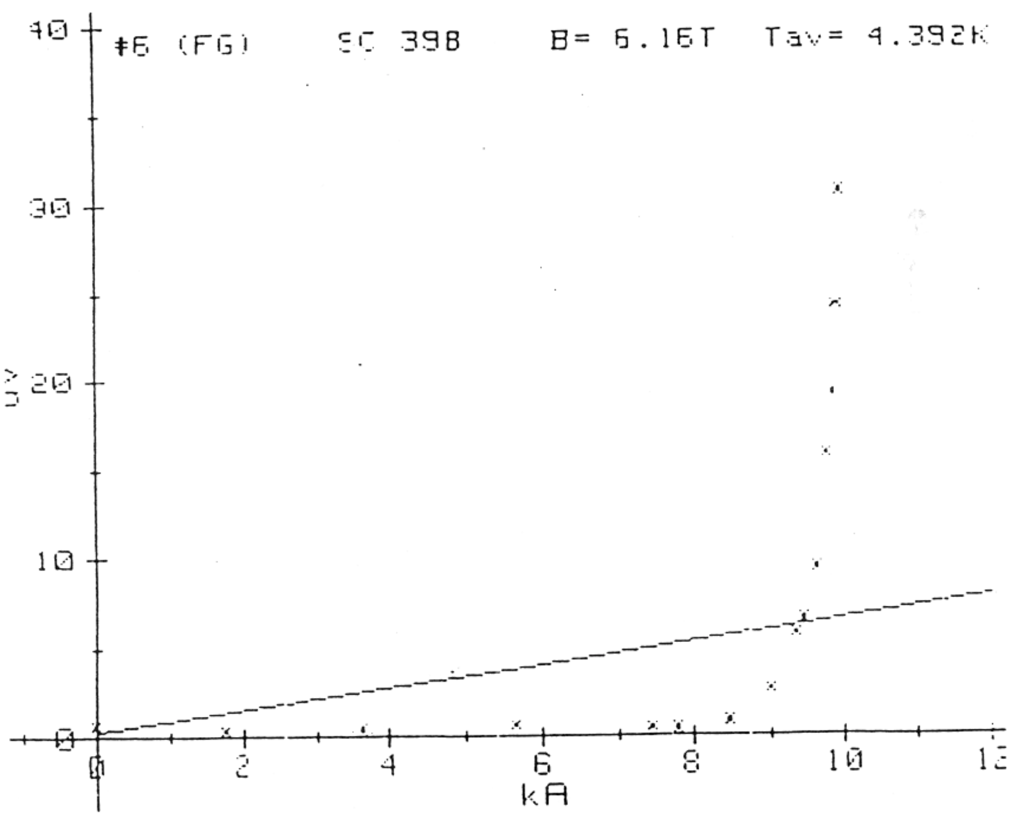

Fig. 1. V-I curve for an SSC inner type cable. Test length - 70.0 cm. See Ref. 13 for physical description of the cable.

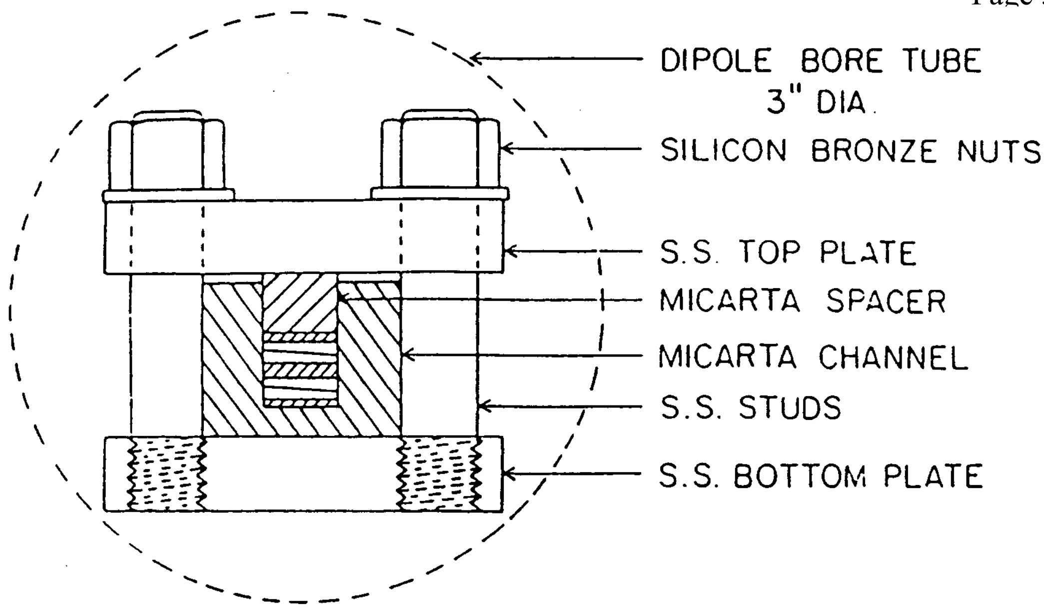

Fig. 2. Mechanical Assembly. Two bifilar pairs of keystoned samples are assembled, as shown. The members of each pair are separated by Kapton, 0.010 in. thick. Instrumentation is located in G-10 strips placed in contact with each sample. The thicknesses of the G-10 strips are 0.030, 0.100, and 0.030 in., respectively. The stainless steel studs are spaced 1.5 in. apart along the 48 in. length of the fixture. The silicon bronze nuts are tightened to 200 in.-lbs. torque resulting in a mean pressure on the samples of approximately 10 kpsi.

CABLE TEST FACILITY

The sample holder discussed above is inserted in a dipole magnet which is 1.2m long and has a 75 mm bore. This is an early R&D dipole which is described in the literature.[8] It has been used continuously for the last 12 years. The maximum central field is a little over 6T.

The liquid helium dewar is 2.8m long and has an inside diameter of 600 mm. Helium is supplied from a 10,000 ℓ storage dewar, which is connected to a 100 ℓ/hr liquefier. Gas recovery, storage, purification, and compression are handled by a central BNL plant.

Thus, the cable test facility consists of four separate areas:

- the gas handling plant
- refrigerator and storage room
- test dewars and power supplies - see Fig. 3
- electronic measurement and controls lab.

It would not be feasible to duplicate this investment in plant and operating cost at each cable vendor's facility. An alternative method of assessing cable performance, which is described below, can more economically serve to provide in-house short sample information to the superconductor manufacturer. Before doing so we describe two examples of quality control results, in the next two sections.

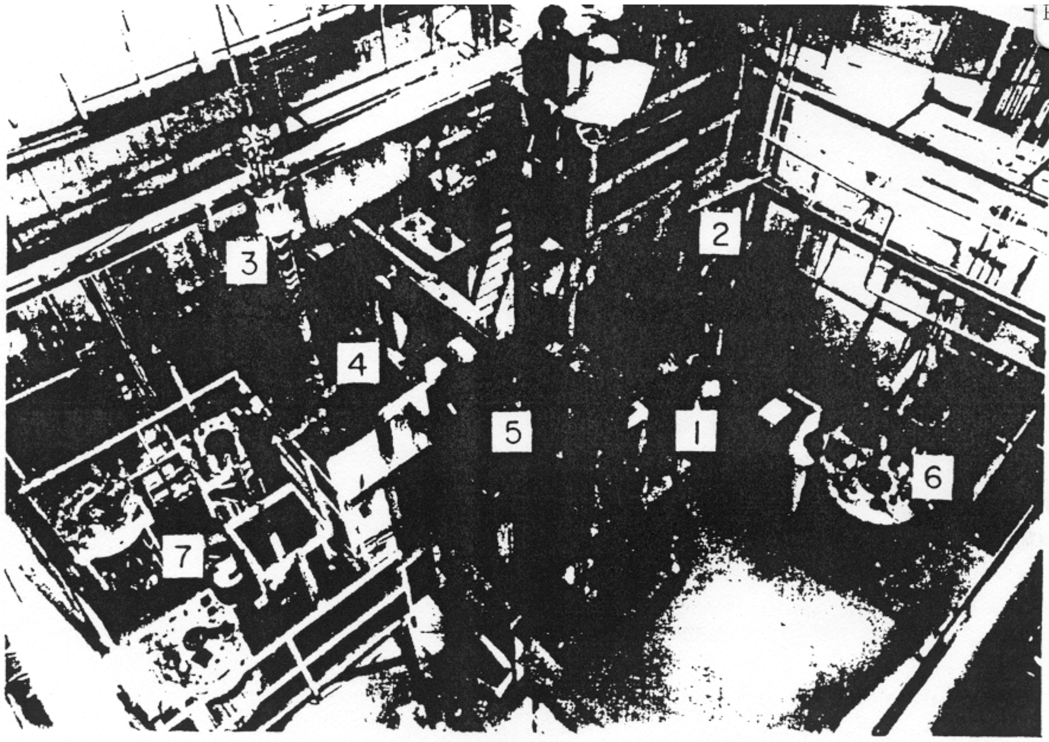

Fig. 3. Dewars and power supplies. 1-test dewar. 2-He fill and recovery lines. 3-sample probe. 4-15 kA power supply. 5-4 kA dipole power supply. 6-magnetization test dewar. 7-assembly area.

REPORTING OF CABLE RESULTS

Figure 4 is an example of the customary quality control report for a cable, in this case the one discussed earlier in connection with Fig. 1. Measurements are made at several fields. The first part of the report lists the peak field, the helium bath temperature, the critical current I_t, the quench current I_q, the quality parameter, n, and the critical current calculated for the reference temperature (4.22K in this case).

The next part lists the results of resistance measurements at room temperature and 10K. These are conveniently measured in the apparatus described. A complete description of the procedure is given elsewhere.[6] The room temperature resistance, R295, is an important element of the cable specification as it is determined by the Cu/SC ratio. Conversely, the Cu/SC ratio may be calculated from the measured resistances. This calculated value and the residual resistance ratio, RRR, are listed.

The last part of Fig. 1 gives critical currents determined by fitting a straight line to the measured I_c-B points. This is a good representation of the I_c-B dependence for fields between 5 and 7T, for multifilamentary NbTi wire of the type used (46.5 wt, % Ti). In making the fit to the cable data the slope is chosen to be the same as for the wire; wire data is usually more accurate since it is averaged over several wires. Special cable tests in which many points are measured and very great care is taken to reduce field and temperature errors confirm that wire and cable slopes agree. For routine production cable testing it is more efficient to measure points at a few fields and utilize the wire slope value. The resulting accuracy is about ± 150A.

Critical current densities are also listed. These are based on the specified or stated strand diameter and on the Cu/SC value determined from the resistance measurements.

Run 2066 SC 398 10/25/88

Measurements

B	T	It	Iq	n	Ic
5.38	4.407	11547	12005	27	12371
5.79	4.406	10166	10826	25	10944
6.16	4.392	9356	9984	24	10064

R(295) = 25.5 uohms/cm RRR= 69
R(10) = .37 " C/S= 1.42

Calculated results for T= 4.22

B	Ic	Jc
5.0	13284	2730
5.6	11614	2387
6.0	10501	2158
7.0	7718	1586

Fig. 4. Short sample test report (same cable as in Fig. 1).

AN EXAMPLE OF CABLE REJECTION

QC test results for several projects have been published.[2,6] From time to time cables are found to be below specification, necessitating diagnosis and correction of the underlying problem. An interesting example of one such case occurred during the production of cables for the HERA project. A detailed review of the complete run including test results for some 300 samples is given in reference 9. Early in the run the sequence shown in Fig. 5 was observed: a downward trend began at No. 28 and culminated in a clearly pathologic cable at No. 34. Fortunately the cabler was shut down at this point for other reasons. Thus, there was time for the manufacturer to investigate the cause, which turned out to be an improperly positioned mandrel. Gradual slippage of the mandrel led to increasing filament breakage and the observed steady decrease in I_c. After correcting this problem, no further difficulties arose during the remainder of the production run.[9]

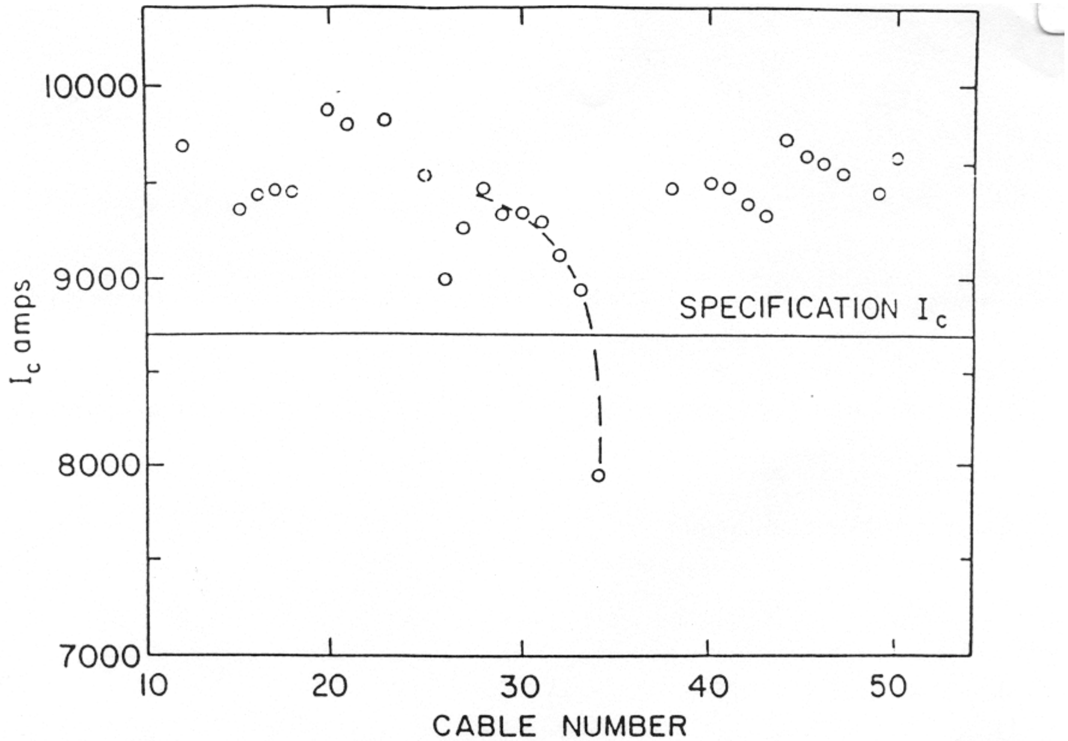

Fig. 5. Critical currents of a sequence of cables during a production run for HERA (cf. reference 9).

ESTIMATION OF I_c FROM EXTRACTED STRAND DATA

Recently it was reported that a good estimate of the critical current of a cable is obtained by summing the critical currents of the strands extracted from the cable.[4] In doing this, the measured strand currents are used with no account taken of wire self field effects (strand measurements are described in Ref. 10). This "rule of thumb" has been tested for cables in which the current, the Cu/SC ratio, and the residual resistance ratio have different values. The results are shown in Table 1. The first four columns list the cable number and the measured values of Cu/SC, RRR, and I_c. Column 5 lists the degradation, D = 100 x (1 - I_c/I_w), where I_w is the sum of the critical currents of the wires used to make the cable. In most of the cases, I_w is approximated by measuring between 8 and 12 wires. The average of these wire values is multiplied by the total number of cable strands to get I_w. In one case, cable 378, all 30 strands were measured because the value of Cu/SC varied considerably from strand to strand. In those cases where D values are not listed, pre-cabling wire samples were not provided. Two samples have zero or negative degradations. These come about partly from sampling error in determining I_w. In addition, neglect of self field effects in wires reduces I_w by a few percent.

The estimated critical current of the cable based on the extracted strand currents, I_{cx} is similarly determined from a sample of strands. In most cases a relatively small number of strands was tested. Column 6 lists the percentage difference between I_{cx} and I_c, and column 7 lists the number of extracted strands, N_x. It appears from Table 1 that with Nx ~ 4 a reasonable estimate, good to about ± 2%, is obtained. Part of the difference between I_c and I_{cx} is due to the accuracy of the cable measurement, which is between 1 and 2% also.

The procedure by which I_{cx} is determined is the same as that by which I_w is determined. By estimating the degradation from wire measurements, i.e., from I_c and I_{cx}, geometrical and other experimental conditions are nearly identical; this is an advantage over the method of comparing wire and cable results. The values of D obtained by comparing I_{cx} and I_c are approximately equal to the differences between the values listed in columns 5 and 6 of Table 1.

A quantitative calculation explaining the rule of thumb would be hard to formulate. For one thing, the magnetic field distributions are quite different for the two measurement configurations, cable vs strand. For another, the voltage distribution along an extracted strand, varying as it does between highly deformed, kinked regions and regions which are only slightly deformed, is rather different from that along the cable." It is fortuitous, therefore, that the rule works as well as it does.

Table 1. Comparison of Cable and Extracted Strand Data (B-5T, T-4.2K).

Sample	Cu/SC	RRR	I_c(amps)	D(%)	$100[I_{cx}/I_c-1]$	N_x
RHIC Types[12]						
106	2.26	66	6660	13.1	2.7	2
107	2.26	66	6880	10.2	1.6	2
SSC Inner Types[13]						
351	1.50	34	11232	5.3	-0.6	8
351A	1.50	130	11621	-	-1.0	16
383	1.60	84	12828	4.0	0.8	3
395*	1.80	70	11130	0.0	-0.3	4
398	1.42	70	13284	-2.4	-1.5	4
399	1.54	82	13693	-	-2.9	4
6135	1.20	105	14160	-	-0.4	4
SSC Outer Types[13]						
369	1.70	68	9600	6.9	1.9	3
378	1.70	74	9160	7.8	1.2	2
380*	1.71	65	9164	5.0	1.5	4
385**	1.59	66	8955	9.3	0.4	30
6136	1.73	110	9660	-	1.1	4
HERA Types[9]						
L383	1.70	77	11973	-	0.0	4
1553	1.80	75	11397	-	-1.0	22

*These cables were made from a single continuous strand.
**This cable was made from strands in which Cu/SC varied from 1.24 to 1.71. All strands, both before and after cabling, were measured.

SUMMARY

A large investment in equipment and refrigeration is needed for cable critical current tests. This makes it impractical for wire and cable manufacturers to undertake such tests themselves. Fortunately, a good estimate of cable critical current can be obtained from extracted strand measurements. A relatively small sample, ~4 strands, is adequate for this purpose. Thus, it is possible to monitor cable production with modest expenditures. Sample cables could be tested at a national facility such as that at BNL in order to ensure the validity of the extracted strand results.

ACKNOWLEDGEMENTS

We thank the cryogenic support group directd by D.P. Brown for their vital support. Many helpful suggestions have been made in the course of this work by K. Robins and A.K. Ghosh. We thank R.K. Maix and A.F. Greene for discussions concerning the HERA cables.

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IEEE TRANSACTIONS ON MAGNETICS, VOL. 25, NO. 2, MARCH 1989

NORMAL STATE RESISTANCE AND LOW TEMPERATURE MAGNETORESISTANCE OF SUPERCONDUCTING CABLES FOR ACCELERATOR MAGNETS*

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Abstract

The normal state resistivity of the superconducting NbTi cable used in accelerator magnets is usually specified by the resistance per unit length at room temperature (295 K) and the residual resistance ratio (RRR). Using these resistance parameters, the amount of copper in the multifilamentary wire can be calculated. This method is consistent with the traditional etch and weigh technique, and as such is a alternative and convenient way of specifying the copper to superconductor ratio. In principle the magnetoresistance can be calculated from the RRR and the "Kohler Plot", for copper. In practice however, measurements of magnetoresistance for a wide variety of SSC inner cables show considerable disagreement with calculation. In this paper the magnetoresistance data on cables with RRR ranging from 50 to 175 are analyzed taking into account the conductor geometry and the effect of the small interfilamentary spacing on the resistivity of copper.

Introduction

The electrical resistance of the multifilamentary NbTi wire which is used to make superconducting magnet cable is routinely measured at 295 K and 10 K. From these two measurements can be determined the amount and purity of the copper in the wire. Similar measurements are also made on the effect of transverse magnetic fields on the normal state resistance of the cable. These normal state resistances are relevant in determining quench propagation characteristics and the maximum temperature reached in the coil windings of a magnet during a quench. In the first part of this paper we discuss the relationship between the room temperature measurement and the amount of copper in the superconducting wire. The second part deals with the transverse magnetoresistance of SSC prototype cables.

Resistance and Copper to Superconductor Ratio, Cu/Sc

In this section we examine the quantitative relationship between the resistance and the copper to superconductor ratio, X. A study of CBA wires with a nominal X of 1.7 has been reported by Garber et. al.[1] In the present report, wires from several sources with X values ranging from 1 to 3 were examined. Resistances and critical currents were measured on 75 cm long samples. Two 25 cm pieces were then cut from each sample for the mass determination as outlined below.

The copper to superconductor ratio is defined in terms of the volumes of the respective components. It can be calculated from four quantities: A, the area of cross section; m, the wire mass per unit length; m_S, the mass of NbTi per unit length, and δ_{cu}, the density of copper. The superconductor mass was determined by weighing after etching away the copper matrix. Each sample was weighed three times: before etching, after a 15 minute etch in 50% nitric acid solution and after a second 15 minute etch, to make certain that all the copper was removed. Weight readings before and after the second etch agreed to with = 0.1 mg. This corresponds to ±0.5% in m_S. The copper to superconductor ratio, X_m, is calculated from,

$$X_m = \left(\frac{A\ \delta_{cu}}{m-m_s} - 1\right)^{-1} \qquad (1)$$

The room temperature resistance R_t is measured at ambient temperature t(°C), and the resistance at the reference temperature of 295 K is calculated from:

$$R = R_t/[1+0.0039\ (t-22)] \qquad (2)$$

The low temperature resistance R_{10} is measured just above the transition temperature of NbTi. The residual resistance ratio r is then defined as

$$r = R/R_{10} \qquad (3)$$

The room temperature resistance can be written as,

$$\frac{1}{R} = \frac{X}{(1+X)}\frac{A}{\rho_{cu}} + \frac{1}{(1+X)}\frac{A}{\rho_s} \qquad (4)$$

or,

$$X = \frac{1 - RA/\rho_s}{RA/\rho_{cu} - 1} \qquad (5)$$

where ρ_{cu} is the copper resistivity at 295 K and ρ_S is the resistivity of NbTi ~ 60 μΩ/cm. Variations in ρ_{cu} due to impurities may be approximated by

$$\rho_{cu} = \rho_i \frac{r}{r-1} \qquad (6)$$

where ρ_i = 1.695 μΩ-cm is the resistivity of pure copper.

If the low temperature resistance is not known a value of ρ_{cu} of 1.71 μΩ-cm can be used which is equivalent to an RRR of approximately one hundred, a typical value for composite wire.

Figure 1 shows the copper to superconductor ratio X_R as derived from resistance measurements plotted against that obtained by mass determination X_m. For some samples $X_R < X_m$ probably due to variations in cross sectional area. This "sausaging" of the filaments has been observed in microstructural studies and is correlated with the low n-values indicative of non-uniform filaments.[2]

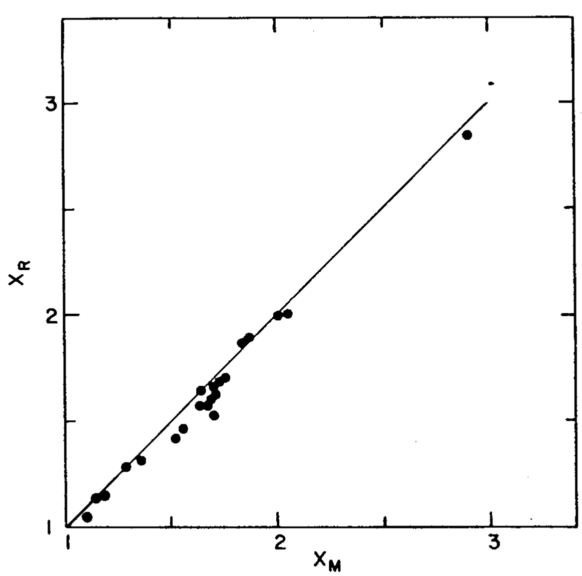

Fig. 1. Resistive determination of Cu/Sc, X_R, plotted versus mass determination, X_m.

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Resistance Specification for Superconducting Wires

Using eq. (5), the resistance of wires of different diameters can be calculated as a function of Cu/Sc ratio. This is shown in Fig. 2 for the wires used in SSC cables. The range of acceptable values of R is determined by the Cu/Sc ratio and wire diameter tolerances. The above calculations can be extended to cables. In applying these formulae the cable resistance is multiplied by N, the number of wires and a length correction factor applied.

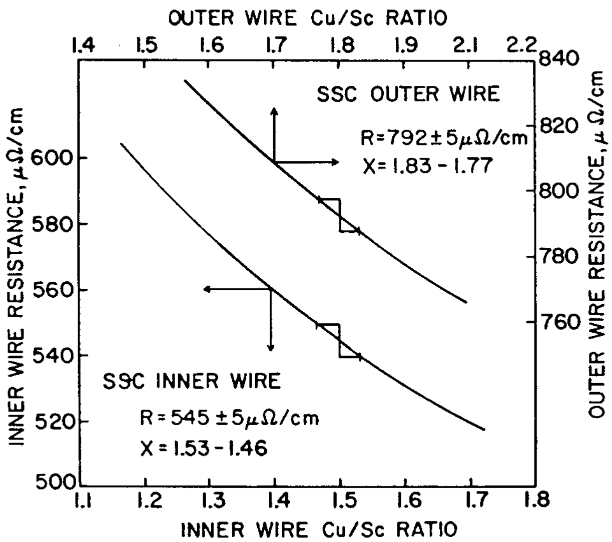

Fig. 2. Plot of resistance per cm for SSC inner and outer wires as a function of copper to superconductor ratio.

Transverse Magnetoresistance of Superconducting Cables

In this section we present magnetoresistance data on some SSC cables. We show that the measurements on conductors with very small NbTi filaments agree with the magnetoresistance of bulk copper provided size effect enhancement of the copper resistivity in the interfilamentary region is taken into account.

Test Procedure for Cables

The room temperature resistance measurement is made using a DC current of 1 A, and voltage contacts 70 cm apart (see Fig. 3). A thermocouple device of 0.1°C accuracy is used to determine the ambient temperature. Temperature correction to 295 K is made using eq. (2).

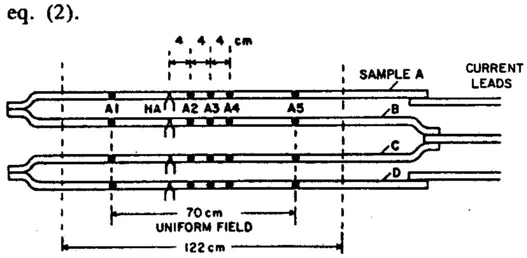

Fig. 3. Electrical wiring schematic experimental arrangement for determination of cable resistance.

The low temperature measurement is a dynamic one, made by inducing a quench when the cable is carrying current. Referring to Fig. 2, a quench is triggered in cable A, for example, by means of heater HA. The resulting waveform observed at nearby voltage taps, A2-A3 or A3-A4, consists of three parts: a superconducting state baseline voltage, a linear ramp voltage corresponding to the passage of the superconducting-normal interface between the voltage taps, and a slowly increasing signal characteristic of the normal state resistance. The latter increases in time due to normal state heating. However, at first the voltage is almost constant and is due to the residual resistance of the copper. Thus, there is a kink in the voltage waveform at the beginning and at the end of the linear ramp portion. The voltage difference between these two points equals the current times the residual resistance of the section of cable between the voltage taps. The resistance per centimeter is determined for two pairs of taps (A2-A3 and A3-A4 in Fig. 3) and averaged. The taps are relatively close to the heater in order to minimize the effect of current fall-off which results from the increase of normal state resistance as the quench propagates.

The above measurement is made at zero field and in an external transverse field in order to determine the magnetoresistance effect. The longitudinal quench propagation velocity can be deduced from the same test.

Experimental Data

Like copper, the magnetoresistance of the cables was found to be linear with field in the range $1 < H < 6$ tesla. Figure 4 shows the data for some of the cables that were studied. Considerable variation in the low temperature resistance is possible even for cables with the same Cu/Sc. Cable SC368A is similar to SC368B except the former was annealed after cabling. Table I lists the cables and their relevant geometric parameters.

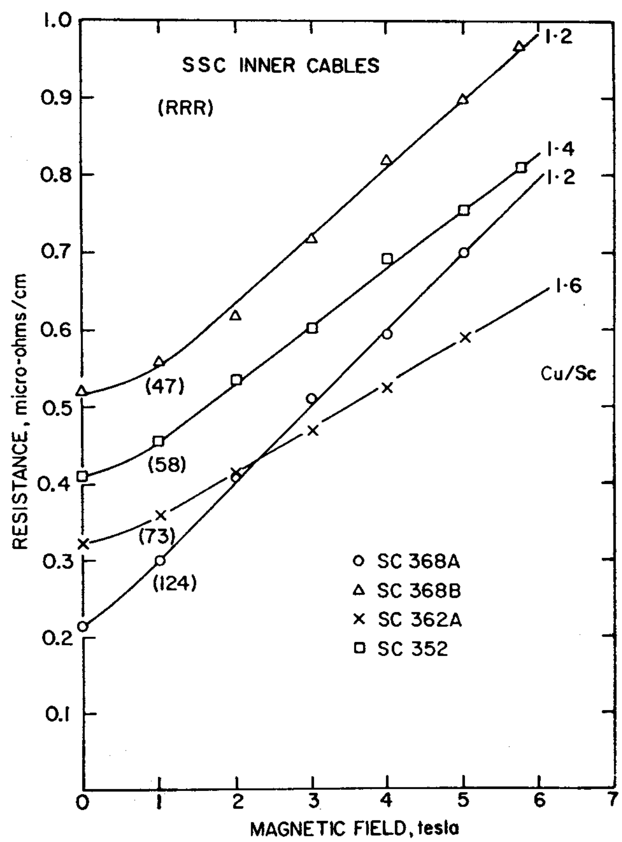

Fig. 4. Resistance per unit length of SSC prototype cables as a function of applied magnetic field.

From a magnet designer's point of view the quantity of interest is the resistance at field which is given in Fig. 5, as the ratio of the resistance of 6T to that at zero field plotted vs the measured RRR. The solid line reflects recent data at 4.2 K for oxygen-free copper as compiled by Fickett.[3,4] Clearly, for the conductors which have filaments with diameters, d ~ 5 μm, the measured magnetoresistance is higher than that predicted by the bulk copper data.

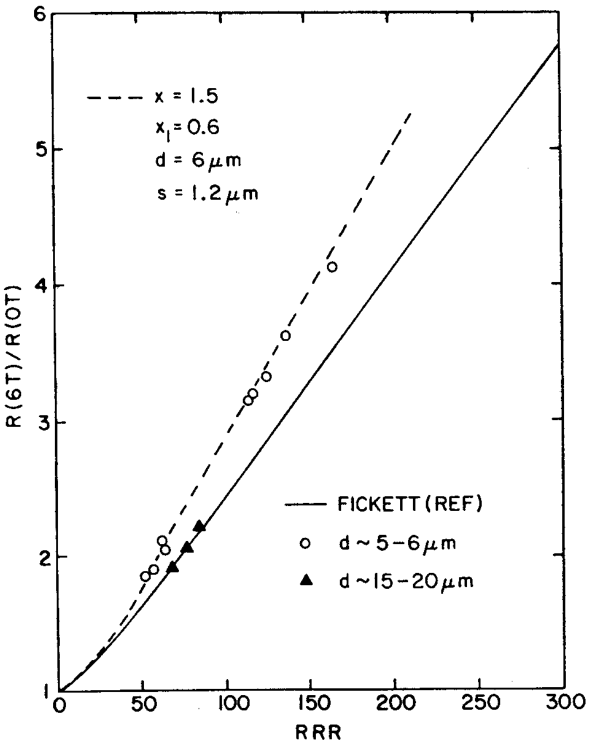

Fig. 5. The ratio of resistance at 6 tesla and at 0 tesla of SSC cables as a function of the measured RRR. The solid line is Frickett's[3,4] data for bulk copper.

Size Effect in Multifilamentary Superconducting Wires

The discrepancy between the predicted and measured values of magnetoresistance can be reconciled by taking into account the resistivity enhancement in copper due to the so called "size effect". This becomes important when the bulk electronic mean free path, ℓ becomes comparable to some sample dimension. The boundary scattering of electrons in effect reduces the scattering length and thereby increases the resistivity. Brändli and Olsen[5] have written a detailed review of this effect and more recently Cavalloni et. al.[6] have presented experimental evidence for the existence of a size effect on the longitudinal resistivity of multifilamentary superconducting wires.

Although there are several expressions for the resistivity enhancement the simplest one, by Nordheim,[5] is the one we shall use. In the copper-stabilized wires there are usually two regions: (a) those which are free of filaments and (b) those consisting of a array of NbTi filaments. The surfaces of the NbTi filaments act as boundary scatterers, and the copper in the interfilamentary region has a higher resistivity when ℓ is greater than the interfilament spacing, S. Assuming diffuse scattering at the NbTi interface, the resistivity of the copper can be represented by;

$$\frac{\rho_1}{\rho_o} = 1 + (1/K)$$

In this case $K \equiv S/\ell < 1$ and ρ_0 is the residual resistivity of (a) and ρ_1 the resistivity of (b). At 295 K, $\ell << S$ and the size effect is unimportant. Equation (7) can be written as:

$$\frac{r_1}{r_0} = \left(1 + \frac{\ell}{S}\right)^{-1} \tag{8}$$

where r_1 is the RRR of region (b) and r_0 is the RRR of the region (a). The mean free path can be calculated from[7] $\rho\ell = 6.56 \times 10^{-12}\,\Omega$ -cm^2. From this the $\ell = 0.0387\ r_0$ μm. Using this in eq. (8) we find that

$$r_1 = r_0\left(1 + \frac{0.0387}{S}\, r_0\right)^{-1} \tag{9}$$

The interfilament spacing, S, is related to the local Cu/Sc ratio, X_L, by

$$X_L = 1.1(1 + S/d)^2 - 1 \tag{10}$$

where S and d, the filament diameter, are in microns. Using the geometric paramenters X, X_L, and d, and the measured value of r, we can calculate r_0 and r_1. These are given in Table I. For large filament conductors similar to those studied by Cavalloni et. al.,[6] the ratio $(r_0/r_1) \sim 2$. However in fine filament conductors with small S values this ratio can be much higher. Thus if the RRR of the bulk copper is 100 the RRR of the copper between the filaments is only 20. Furthermore if the bulk copper is improved to 200 by annealing the interfilament copper ratio only increases to 23 for a conductor with a one micron filament spacing. A simple calculation leads to the residual resistivity ratio of the composite:

$$r = \left[(X - X_L)\ r_0 + X_L r_1\right]/X \tag{11}$$

and r is always less than r_0

Now if we assume that in field, the copper increases in resistivity in accordance with its respective RRR, then the ratio of the resistance at 6 tesla to that in zero field can be determined by reference to the bulk copper curve of Fig. 5. The dashed curve in Fig. 5 was calculated for X = 1.5, X_L = 0.6, S = 1.2 μ and d = 6 μ,

Table

Cable Sample	Wire Dia. mm	Cu/Sc,X	Filament Dia. μm	Local Cu/Sc,X_L	RRR r	RRR r_0	RRR r_1	r_0/r_1	S μm	R(6T)/R(0T) Meas.	R(6T)/R(0T) Cal.
SC357	0.81	1.45	5	0.45	166	232	17.9		0.75	4.12	4.20
SC368A	0.81	1.2	6	0.50	125	198	22.8		1.0	3.32	3.47
SC368B	0.81	1.2	6	0.50	53	77	19.3		1.0	1.85	1.85
SC368B1	0.81	1.2	6	0.50	136	248	27.5		1.0	3.65	3.70
FG6218	0.81	1.28	4.7	0.45	116	171	16.6		0.7	3.20	3.26
SC363	0.81	1.6	20	0.45	79	94	46		3.0	2.01	2.14
SC347A	0.81	1.33	5	0.8	115	241	31		1.4	3.15	3.39
SC347A1	0.81	1.33	5	0.8	57	102	26.7		1.4	1.90	1.96
SC352	0.81	1.60	5	0.45	62	80	15.6		0.75	2.10	2.00
SC362	0.81	1.40	6	0.5	64	89	20		1.0	2.05	2.04
XT-12	0.81	1.3	23	0.8	69	86	58		6.9	1.90	1.94
SO118	0.65	1.8	15	0.6	84	104	44		3.0	2.20	2.25

the parameters for the SSC inner cable. Measured values of the R_6/R_0 ratio for conductors of this type, the open points in Fig. 5, agree with the calculated curve to a remarkable degree. Conductors with larger filaments and therefore larger filament spacing, the solid points, are almost indistinguishable from bulk copper.

Conclusions

Resistance measurements which are rountinely made on superconducting wires and cables for accelerator magnets can provide an accurate measure of the copper to superconductor ratio. Compared to the etch and weigh technique a resistance specification for Cu/Sc is preferable for monitoring of this parameter during wire and cable production.[8]

Results shown here indicate that by using the 4 K magnetoresistance data of bulk copper and the size effect formula for the resistivity enhancement of copper, the measured RRR can be used to estimate the resistance at high fields.

Acknowledgements

We than Dr. R.P. Shutt for several discussions and for initially pointing out the discrepancy from the "Kohler Plot".

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THE EFFECT OF SELF FIELD ON THE CRITICAL CURRENT DETERMINATION OF MULTIFILAMENTARY SUPERCONDUCTORS*

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Abstract

In determining the short sample critical current of conductors of large cross section or high current density the self field produced by the transport current must be taken account in order to obtain a "true value" for the critical current. A simple model calculation for determining this effect is described. Measurements on wires, cables, and monoliths show the validity and self consistency of the procedures.

Introduction

It has been known from the earliest days of superconductivity that the self field plays a role in the determination of the transport critical current, I_c. Since the self field is proportional to the current it is especially important in connection with modern high current conductors. Frequently, little account is taken of this in the reporting of critical current data. This is probably due to the fact that modern conductors are complicated configurations of twisted filaments and/or wires, and an exact calculation of the self field would be formidable if not impossible. In an earlier paper[1] we described a simple model calculation of the self field of an accelerator magnet (Rutherford type) cable. Since then experience has shown that the application of this simple procedure gives currents which are self consistent in a number of ways. For example, the results are independent of the short sample test geometry. This is important in reporting results for quality control purposes. Likewise, comparison of short sample results with magnet performance is found to be in much better agreement.

In this paper we describe the application of our method to several multifilamentary NbTi conductors: wires, SSC type cables, and a monolithic conductor of rectangular cross section. In each case the magnetic field in a plane normal to the direction of current flow is calculated assuming the current to be distributed uniformly over the entire cross section of the conductor. In the case of the cable the cross section is taken to be the trapezoidal figure enclosing all the wires. The magnitude of the peak field resulting from the sum of the applied field, B_a, and the self field is called B_p. An important assumption we make is that the proper field to be used with the measured critical current is the peak field, B_p, rather than the applied field or the average field.

The critical current is defined as the 10^{-12} ohm cm value at T = 4.222 K. The experimental method for determining I_c is described elsewhere.[2,3,4] A preliminary discussion of the self field correction was given at the 1986 ICFA meeting.[2]

Multifilamentary Wires

Wires are generally measured in the form of coiled samples with relatively wide spacing between turns. The peak field at the wire surface is, to a good approximation:

$$B_p = B_a + 4 \cdot 10^{-4}\ I / D$$
$$= B_a + \pi \cdot 10^{-4}\ JD/(1+x) \qquad (1)$$

where B is in tesla, I in amperes, and D, the wire diameter, is in mm. J is the current density in the superconductor in A/mm^2, and x is the copper-to-superconductor ratio. Figure 1 shows the application of this formula to critical current data for a multifilamentary wire of the type used in SSC cables.[5] The lower curve shows the I_c data plotted versus B_a-values; the upper solid curve is a plot of the same data versus the B_p-values. The open circles in Figure 1 show the results of magnetization measurements of J_c at a number of fields. The experimental details of the magnetization measurements are given in reference 6. J_c is calculated by means of the Bean-London formula:

$$J_c = 1.9 \cdot 10^6 \cdot (1+x)\Delta M/d \qquad (2)$$

where ΔM is the width of the magnetization loop in tesla and d is the filament size in µm. The magnetization data agree well with the self field corrected transport data. Filament sausaging is small in this wire so that differences between the transport and magnetization currents mentioned by Wilson[7] are not discernible in this sample. The high field differences are attributed almost entirely to the self field effect. The dashed curve in Figure 1 is an extension of the critical current curve into the low field region where it is not accessible to transport current measurements because of the self fields.

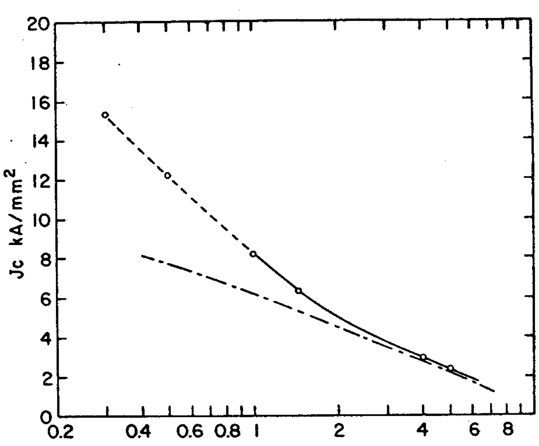

Fig. 1. Critical current density in a wire with D = 0.65 mm, C/S = 1.8, filament dia. = 5 µm, n-value = 25 at 5T.
(– · · · –) transport J_c plotted aginst B_a.
(————) transport J_c plotted against B_p.
(O O O) J_c calculated from D.C. magnetization.

Equation 1 shows that the self field effect is proportional to D and J_c. this is illustrated in Figure 2 for a range of values common in practice. The ratio of self field corrected critical current density, J_{sf}, to the uncorrected value, J_a, is plotted against J_a for wires of diameter 0.1, 0.5, and 1.0 mm. The copper to superconductor ratio is assumed to be 1.5 and the ratio of J_c at 5T to J_c at 6T is assumed to be 1.25. For fine wires the correction is negligible but for wire sizes of the order of 1 mm the correction is considerable. An illustration of the size effect is shown in Figure 3. Results are shown for a group of wires which were drawn down as part of a J_c-maximization study. The critical current density is plotted against true strain after the last heat treatment. The larger conductors show relatively lower currents when no self field correction is made. After making the correction J_c varies smoothly with strain. Not only is it more difficult to produce high J_c's in larger wires, but an additional penalty is paid in reporting the results if the self field correction is omitted.

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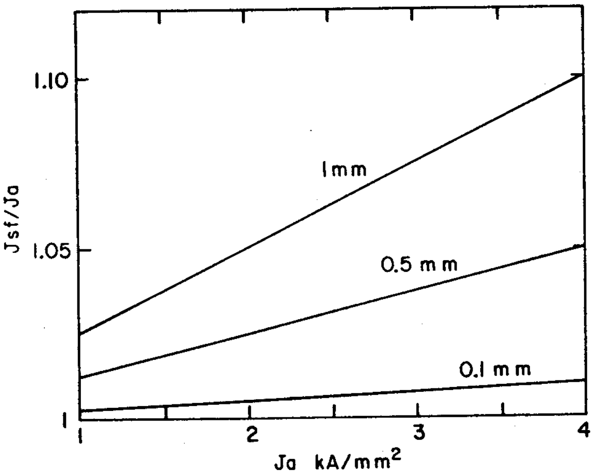


Fig. 2. Self field correction as a function of J_c for various wire sizes. C/S = 1.5, $J_c(5T)/J_c(6T)$ = 1.25.

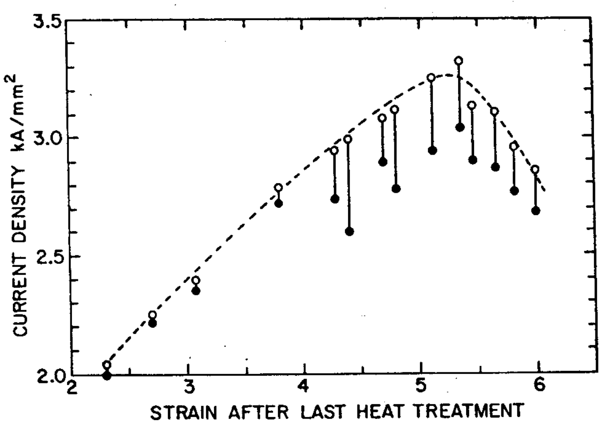


Fig. 3. Critical current density vs strain for wires of different diameters: ● : J_a-(uncorrected values at 5T). O: J_c-(corrected values). The length of the vertical line for each wire is the self field correction. It is proportional to J_c×D.

Cables

The higher currents in cabled conductors lead to a qualitative as well as quantitative difference in the technique of measurement. This is due to the large Lorentz forces which occur so that great care must be taken to constrain the cable samples. An advantageous way to do this is to make the sample straight and bifilar in form. It is then clamped in a stainless steel holder.[2,3,4] The external field is supplied by means of a superconducting dipole magnet. A sample length of 1 m provides adequate sensitivity. Figure 4 illustrates the sample geometry. Usually, two sample pairs are assembled, as shown; measurements are made on one pair at time. Details of the electrical measurements and of the clamping fixture are given in references 2-4.

The applied field is usually oriented either parallel or perpendicular to the cable, i.e., to the wide dimension of the cable. In the parallel case the self field in the gap between the conductors either adds to the applied field, in which case B_p is located along the inner edge, or subtracts from the applied field, in which case B_p is located along the outer edge. This is illustrated in Figure 4 by the points labelled B_p(II,+) and B_p(II,−), respectively. In the perpendicular case the peak fields are located along the edges, where the self and applied fields are in the same directions. The direction of the current flow determines whether B_p is located along the thick or thin edges, see Figure 4.

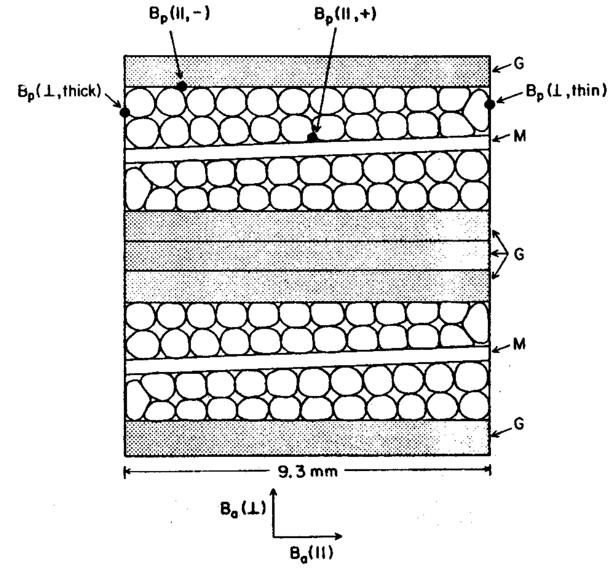


Fig. 4. Arrangement of cable samples in a short sample test. The bifilar pairs are tested separately. The locations of the peak fields are shown for one cable.
B_p(II,−): B_a and self field add on outside surfaces.
B_p(II,+): B_a and self field add on inside surfaces.
B_p(⊥,thin): B_a and self field add along thin edges.
B_p(⊥,thick): B_a and self field add along thick edges.
M: 0.25 mm mylar separators.
G: 0.8 mm G-10 strips which contain instrumentation.

The self fields have been calculated using the complex variable method of Beth.[8] Some results of these calculations are shown in Figures 5-7. Contours of constant field magnitude are shown superimposed on an outline of a bifilar cable pair for the (II,+) and (⊥,thin) cases in Figures 5 and 6, respectively. The quantity $(B_p-B_a)/I$ is referred to as the self field parameter, (B/I) for short. Figure 7 shows a plot of this parameter for the various geometries of interest. Since the peak field generally occurs at a point where the applied and self fields are simply additive the self field parameter is essentially constant over all but the lowest fields. For large gap separations the (B/I) values go to those appropriate for a monofilar conductor test.

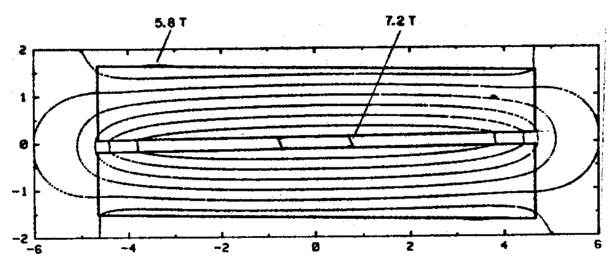


Fig. 5. Constant magnitude field contours for a bifilar pair of SSC cables in the (II,+) configuration. B_a = 6T, I = 10 kA, dimensions in mm. See reference 5 for a detailed description of the cable.

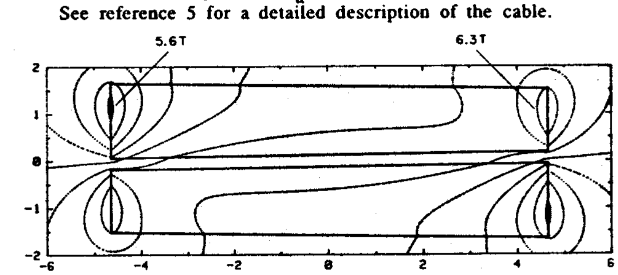


Fig. 6. Constant magnitude field contours for a bifilar pair of SSC cables in the (⊥,thin edge) configuration. B_a = 6T, I = 10 kA, dimensions in mm. See reference 5 for a detailed description of the cable.

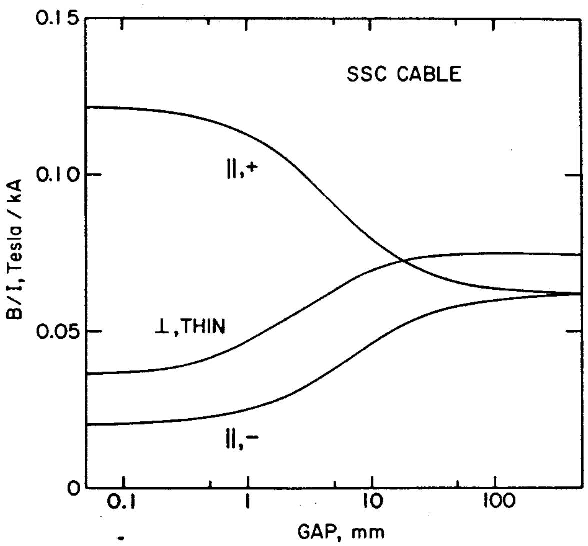


Fig. 7. Variation of the self field correction parameter, $(B_p - B_a)/I$, vs bifilar gap for SSC type cables. For gaps ≥ 100 the self fields are equivalent to those of monofilar samples.

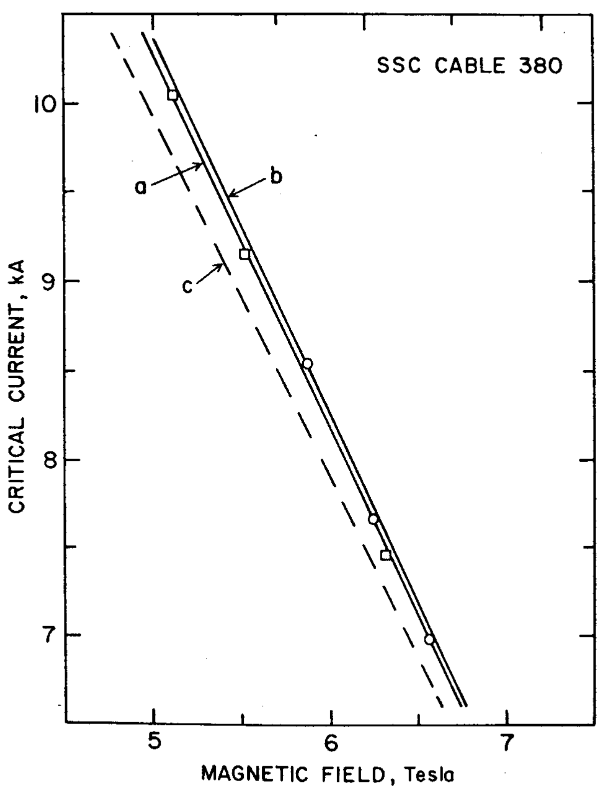


Fig. 8. Critical current in a 30 wire SSC cable made from a single spool of wire with D = 0.5 mm, C/S = 1.75
(a) Cable I_c vs B, parallel orientation. O : (||,+) □: (||,−)
(b) Wire I_c×23 vs B, self field corrected.
(c) Wire I_c×23 vs B, uncorrected.

All the wires in the cable pass repeatedly through the peak field region in a given experiment. As mentioned above, we hypothesize that the critical current of the cable is determined by the properties of this region and the calculated peak field. An exception to this occurs if another region of the cable is sufficiently damaged that the critical current is limited by it even though the field is lower there; however, this does not happen under usual manufacturing practice.

Figures 8 and 9 show the validity of these ideas. The cable tested was made from a single spool of wire so that comparison with the properties of the pre-cabled wire could be made unambiguously. Curve (a) of Figure 8 shows (||,+) and (||,−) data for three applied fields. The I_c values are plotted vs the peak fields and fall on a single line even though the self field parameters are quite different. Note that points from the (+) and (−) configurations overlap. Curves (b) and (c) show how curve (a) compares with wire data. (c) is the critical current curve for the wire (multiplied by the number of wires in the cable) plotted without self field correction, i.e., vs B_a. It lies well below curve (a). However, the corrected curve, (b), lies just above (a). The small difference, about 1%, may be due to measurement inaccuracy, error in the method of correction, or degradation in the cable, but it is clear that these are all small. the wire in the flat region of the cable experiences very minor deformation and it is, therefore, very reasonable that cable and wire data agree. This behavior is found to be true for all wire and cable measurements when the wire data is known and can be averaged properly.

Figure 9 shows results for the two perpendicular configurations together with the parallel results. Since the wires experience consider mechanical deformation in the edge regions the critical currents for these test configurations are generally lower. The thin edge deformation is the severest and I_c the lowest. For this reason, and because the maximum field in a dipole magnet winding occurs near the thin edge (see below), the (⊥,thin) value of I_c, curve (c), is

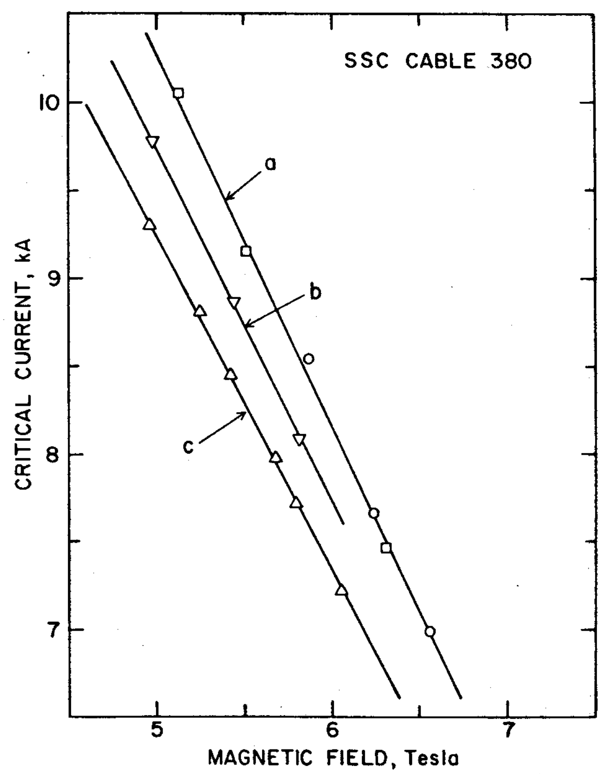


Fig. 9. Critical currents in a 30 wire SSC cable made from a single spool of wire with D = 0.5 mm, C/S = 1.75
(a) Parallel field orientation
(b) Perpendicular field; B_p is located on the thick edge
(c) Perpendicular field; B_p is located on the thin edge

specified for predicting magnet performance. The difference between the wire I_c, curve (b) of Figure 8, and this curve is the cable degradation. In the present example it is 11%. Often a degradation value is cited which is based on the as-measured, i.e., uncorrected, critical current of the wire. This value is always less than the true degradation (and even comes out negative sometimes). In the present example it is 7% or 4% less than the true degradation.

The $I_c(\parallel) - I_c(\perp)$ difference in a cable is thus attributable to the different regions which are sampled in the two measurements. It is not an anisotropy in the usual sense.

An interesting relationship has been observed between the critical currents of wires removed from a cable and the perpendicular thin edge current. When the uncorrected 10^{-12} ohm cm currents are summed for all the wires, a value which is very close to the true cable current is obtained. This "Rule of Thumb" appears to apply for all cables studied irrespective of the degree of degradation. Thus, it is possible to estimate the cable current by testing several wires taken from the cable. It should be noted that this rule works despite the complex voltage pattern along such wires which results from the severe kinking due to cabling. This is not the same I_c as is measured in virgin wires.

Table I lists results for two cables which illustrate the correlations discussed in this section. Although the Cu/SC ratios are the same the two cables are made of different wire and have different geometries. The solid lines indicate the correspondence between parallel cable and self field corrected wire I_c's. The dashed lines indicate the rule of thumb just discussed, viz., as-measured I_c's of wires removed from a cable agree with perpendicular cable values. This rule is seen to be obeyed even the degradations are rather different, 11% for the first, and 6% for the second cable. In the latter case, incidentally, use of the uncorrected wire I_c's would lead one to calculate zero degradation.

Table I

Comparison of cable critical currents with wires before and after cabling. J_c values are given in parentheses. Cu/SC=1.8 B=5T T=4.22K

Wire Sum:	SSC Outer Type	Expt'l Inner
Self field corrected	10370 (2890)	11900 (2830)
Precabling, as meas'd	9990 (2780)	11110 (2650)
From cable, as meas'd	9300 (2590)	11100 (2650)
Cable:		
Perpendicular	9250 (2570)	11150 (2670)
Parallel	10300 (2870)	11960 (2850)

Monoliths

Multifilamentary monoliths of rectangular cross section are often used to make MRI magnets. I_c specifications usually refer to the parallel configuration because these conductors are wound into solenoidal coils. It is convenient to use the same measuring arrangement as for the cables. As the monoliths are somewhat smaller than the cables it is possible to vary the ratio of gap to conductor width over a greater range, and hence the self field parameter also. Figure 10 shows a plot of (B/I) for the monolith studied. Experimental results for two gap separations are shown in Figure 11. At each applied field I_c is determined four times: for the two gaps and two current directions. Four different (B/I) values correspond to the measured I_c's. The self field corrections are indicated by the dotted lines in Figure 11. The points for all four configurations and for all of the applied fields fall nicely on a single I-B curve, which can be considered to be the characteristic curve for this orientation. Thus the self field corrections give consistent results for a wide range of currents and geometries.

The perpendicular data are shown in Figure 12. They are not as interesting since the (B/I) values vary much less for the two gaps. They are 15% lower than the parallel, probably due to a genuine anisotropy effect.

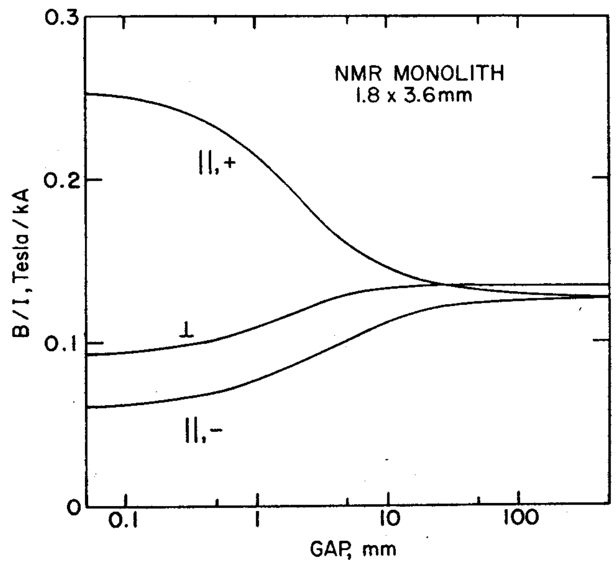


Fig. 10. Variation of the self field correction parameter $(B_p - B_a)/I$ vs the bifilar gap for a bifilar pair of monoliths.

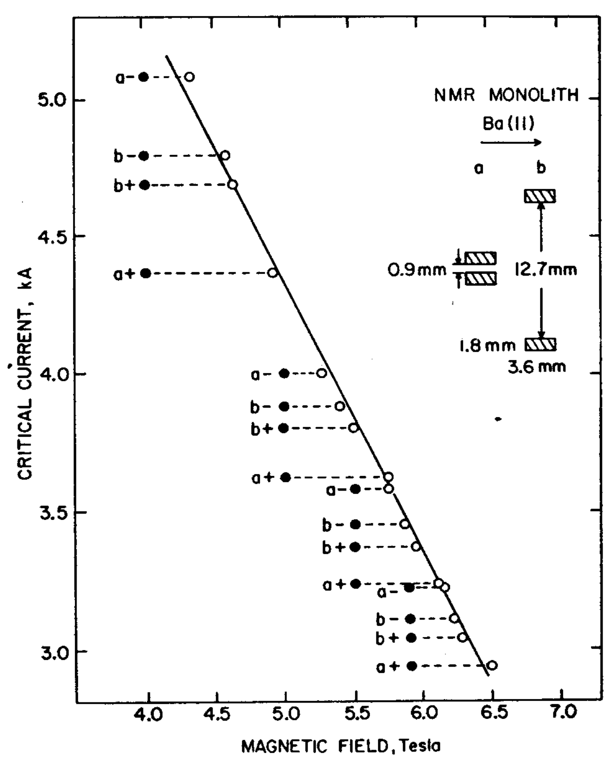


Fig. 11. Parallel field critical current for a bifilar pair of monoliths for combinations of two gap separations and both directions of current. ●: critical current plotted at the applied field, B_a. O: critical current plotted at the peak field, B_p. Horizontal dashed lines represent the self field correction.

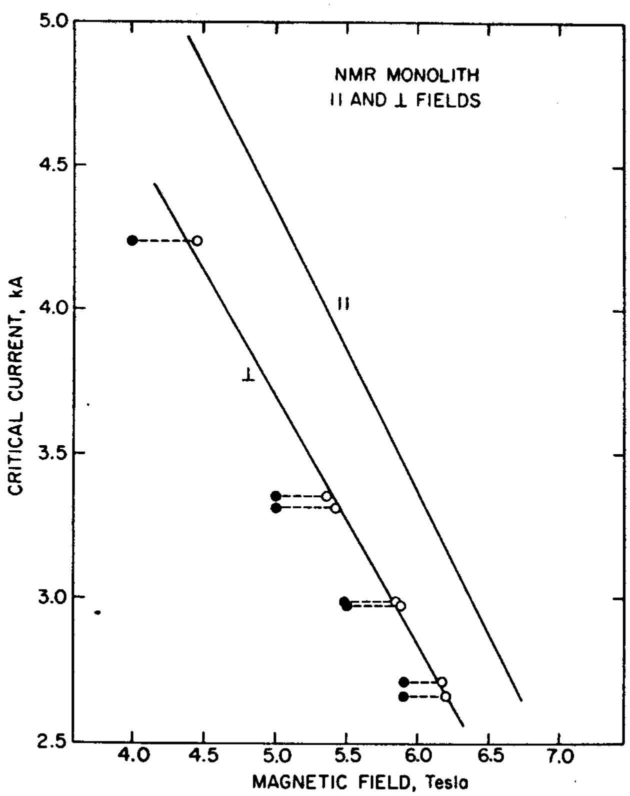


Fig. 12. Perpendicular field critical currents for a bifilar monolith pair for gaps of 0.9 and 12.7 mm.

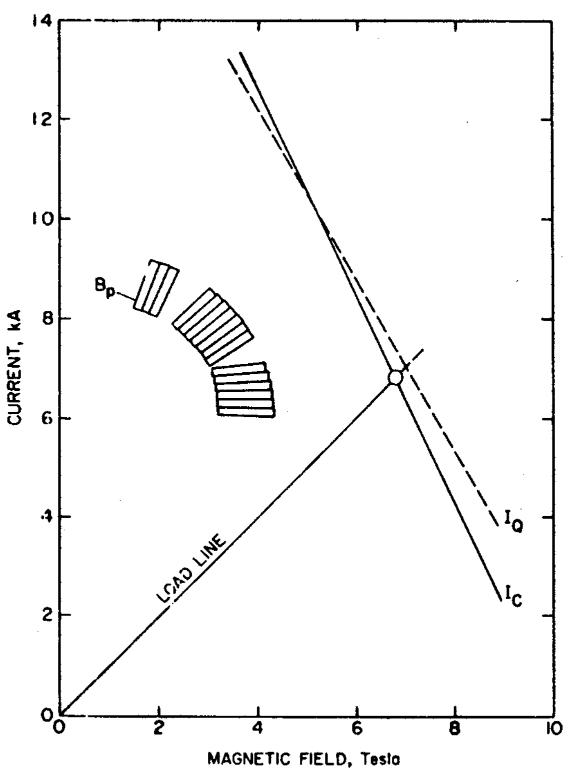


Fig. 13. Load line and cable short sample data, I_c, for a 1.8 m model SSC dipole magnet. I_Q is the quench current observed in the short sample test. Inset: schematic of one quadrant of the inner winding layer showing the location of the peak field in the magnet. The dipole axis is vertical.

Discussion

The self field corrections described in the foregoing sections enable the characteristic $I_c(B)$ curve to be determined consistently for a variety of geometries. This procedure is useful in materials studies such as J_c optimization and cabling degradation, in quality control and purchase specifications, and in comparisons of short sample data with magnet performance. It should be noted, however, that predicting the performance of a device such as a dipole magnet is more complicated than a simple comparison with the short sample I_c value. This is due primarily to the fact that the quench current, I_Q, is not related to I_c in a simple way. Figure 13 illustrates this for short sample measurements of SSC type cables. At high fields and relatively low currents the conductor can carry considerably in excess of the 10^{-12} ohm cm current, while at low fields quenching takes place before the relatively high I_c's are reached. In addition, the peak field in a magnet does not occur exactly at the same point as in the short sample test set-up. The inset of Figure 13 shows a schematic of one quadrant of the inner winding of an SSC dipole. The calculated peak field is seen to occur near, but not quite at the thin edge of the polar turn. Thus a slightly higher performance may be expected than is indicated by the load line-short sample intersection.

The successful identification of measured I_c's with the peak field has the important physical implication that current transfer between filaments is very small over lengths of order 1 m. Otherwise, I_c would reflect a dependence on the average fields in the conductor rather than on the peak fields. The same conclusion applies to current sharing between wires in a cable. It is indeed observed in our 1 m test apparatus that when an individual wire of a cable contains a cold weld splice the critical current of the cable is reduced by the amount that wire would normally carry.[9]

References

[1] M. Garber and W.B. Sampson, "Critical Current Anisotropy in NbTi Cables", IEEE Trans. Magn., Vol. MAG-21, pp. 336-338, March 1985.
[2] W.B. Sampson, "Procedures for Measuring the Electrical Properties of Superconductors for Accelerator Magnets", Proceedings of the ICFA Workshop on Superconducting Magnets and Cryogenics, Brookhaven National Laboratory, Publication No. 52006, pp. 153-156, May 1986.
[3] A.K. Ghosh, M. Garber, K.E. Robins and W.B. Sampson, "Training in Test Samples of Superconducting Cables for Accelerator Magnets", Proceedings of 1988 Applied Superconductivity Conference (this volume).
[4] M. Garber and W.B. Sampson, "Test Methods for Cable Critical Currents and Normal State Resistance", SSC Technical Note No. 70, Brookhaven National Laboratory, March 1988. (unpublished)
[5] "NbTi Superconductor Cable for SSC Dipole Magnets", SSC Material Specification No. SSC-MAG-M-402, June 1987.
[6] A.K. Ghosh, K.E. Robins, and W.B. Sampson, "Magnetization Measurements on Multifilamentary Nb_3Sn and NbTi Conductors", IEEE Trans. Magn., Vol. MAG-21, pp. 328-331, March 1985.
[7] M.N. Wilson, Superconducting Magnets, Oxford Univ. Press, 1983. cf. p. 247.
[8] R.A. Beth, "Evaluation of Current-Produced Two-Dimensional Magnetic Fields", J. Appl. Physics Vol. 40, pp. 4782-4786, November 1969. A Fortran program, "AFLD2", by G. Morgan was used.
[9] M. Garber and W.B. Sampson, "Short Sample Results for Cable S/C 374. The Effect of Cold Welds". SSC Technical Note No. 74, Brookhaven National Laboratory, April 1988. (unpublished)

Test Method 4141-5 - Measurement of Superconductor Cable Interstrand Resistance

A. Scope:

An electrically resistive path is established between individual wires of a superconductor cable by virtue of the wires contacting each other. The value of the resistance between these wires is dependent on the surface condition of the wires and the compressive force of the wires against each other.

The accompanying procedure describes a method of measuring the interstrand resistance of a 30 wire superconductor cable as used for coils in the RHIC dipole magnet. An average resistance value is determined by taking ten (10) measurements from a cable sample at liquid helium temperature.

B. Equipment Required:

1. Superconductor cable sample - Use two pieces of superconductor cable, 5.0 in. long with the outer Kapton film and fiberglass tape insulation removed 1.0 in. from both ends. Tape the two pieces together so that their resultant cross-section is rectangular. Figure 4141-5#1 shows the sample cross-section.

   The 1.0 in. long ends remain untaped and the individual wires are separated for accessibility.

2. Compression Fixture - Consists of a clamp actuated by torquing nuts on threaded rods. Anvils apply pressure across the central 3.0 in. length of cable sample. See Fig. 4141-5#2.

3. 10.0A power supply.

4. Digital Voltmeter.

5. Cryostat filled with liquid He.

C. Procedure:

1. At one end of the two cable pieces of the sample, solder current (I) and voltage (E) leads to every sixth wire end. Figures 4141-5#1 and #3 illustrate the wires and leads that are soldered. Identify each soldered superconductor wire from "1" to "5" as indicated.

NOTE: Each soldered wire will be considered the common connection, in turn, after measurements are made from the common to the other wires. Figure 4141-5#3 indicates wire 1 as the common.

2. Check that soldered connections are satisfactory by apply current and measuring voltages across the identified wires.

3. Place the cable sample in the compression fixture so that the insulated 3.0 in sample length is clamped between the anvil. Apply 4000 psi pressure to the cable sample.

NOTE: This value of pressure is sufficient to determine the interstrand resistance at pressures that the cable will be subjected to in use. This can be seen from the plot of Pressure (psi) vs. Resistance (μΩ), Fig. 4141-5#4, which indicates that interstrand resistance levels off to a singular value after pressure of 2000 psi, approximately.

4. Submerge the fixture into the cryostat filled with liquid He.

5. Measure voltages between all identified wires at 0.0A and 10A with each wire being the common. The voltage measured at 10A is corrected by the residual voltage, if any, measured at 0.0A current. See sample Data Sheet.

6. Plot of applied pressure (X) vs. average interstrand resistance (Y) can now be obtained..

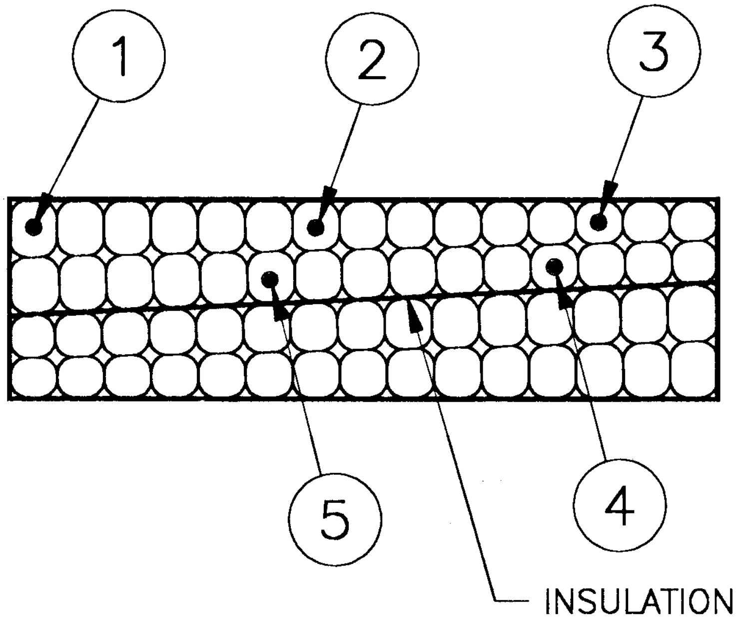
Data Sheet (Sample)

Applied Pressure = 4000 psi.

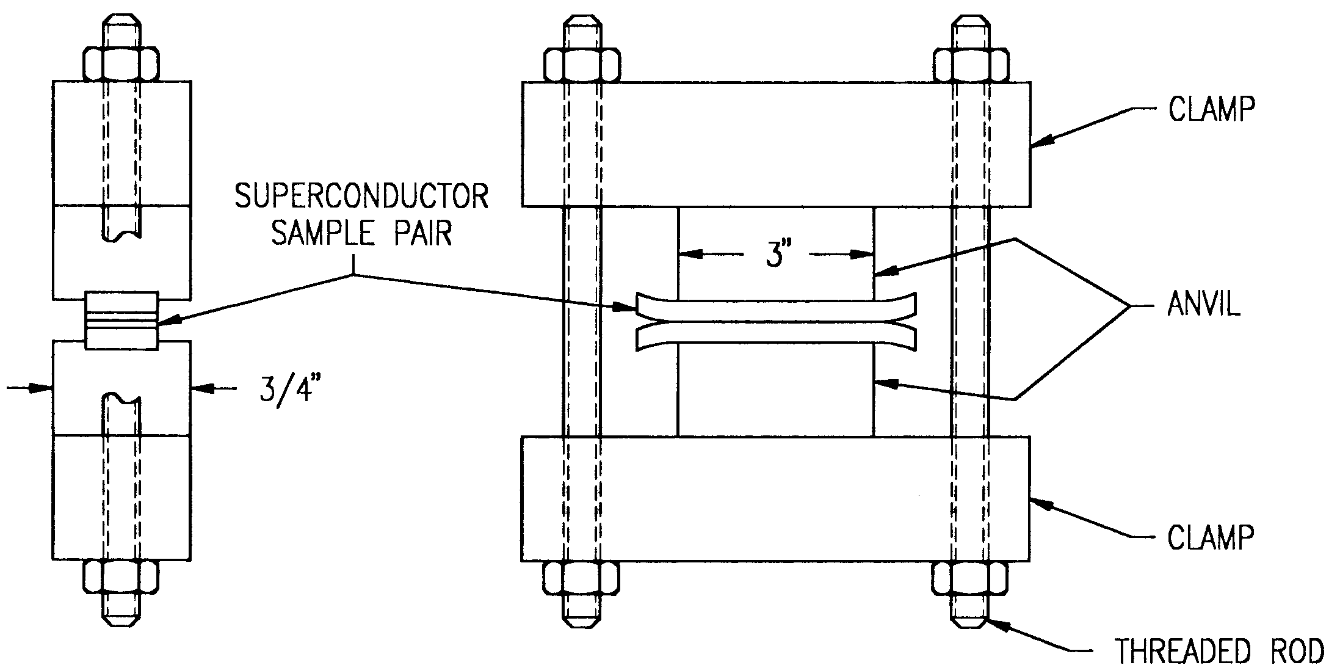
No.	Current Connection #		Volt Conn.#	ΔV at:		ΔV_c (Corrected ΔV)
				0.0A	10A	
	Common	(I)	(E)			
1	1	2	1-2			
2		3	1-3			
3		4	1-4			
4		5	1-5			
5	2	3	2-3			
6		4	2-4			
7		5	2-5			
8	3	4	3-4			
9		5	3-5			
10	4	5	4-5			

$$\Delta V_c(\text{average}) = \frac{\Sigma \Delta V_c}{10}$$

$$R(\text{average}) = \frac{\Delta V_c(\text{average})}{10.0\text{A}}$$



CROSS–SECTION OF CABLE SAMPLE
FIGURE 4141–5 #1



INTERSTRAND RESISTANCE COMPRESSION FIXTURE
FIGURE 4141–5 #2

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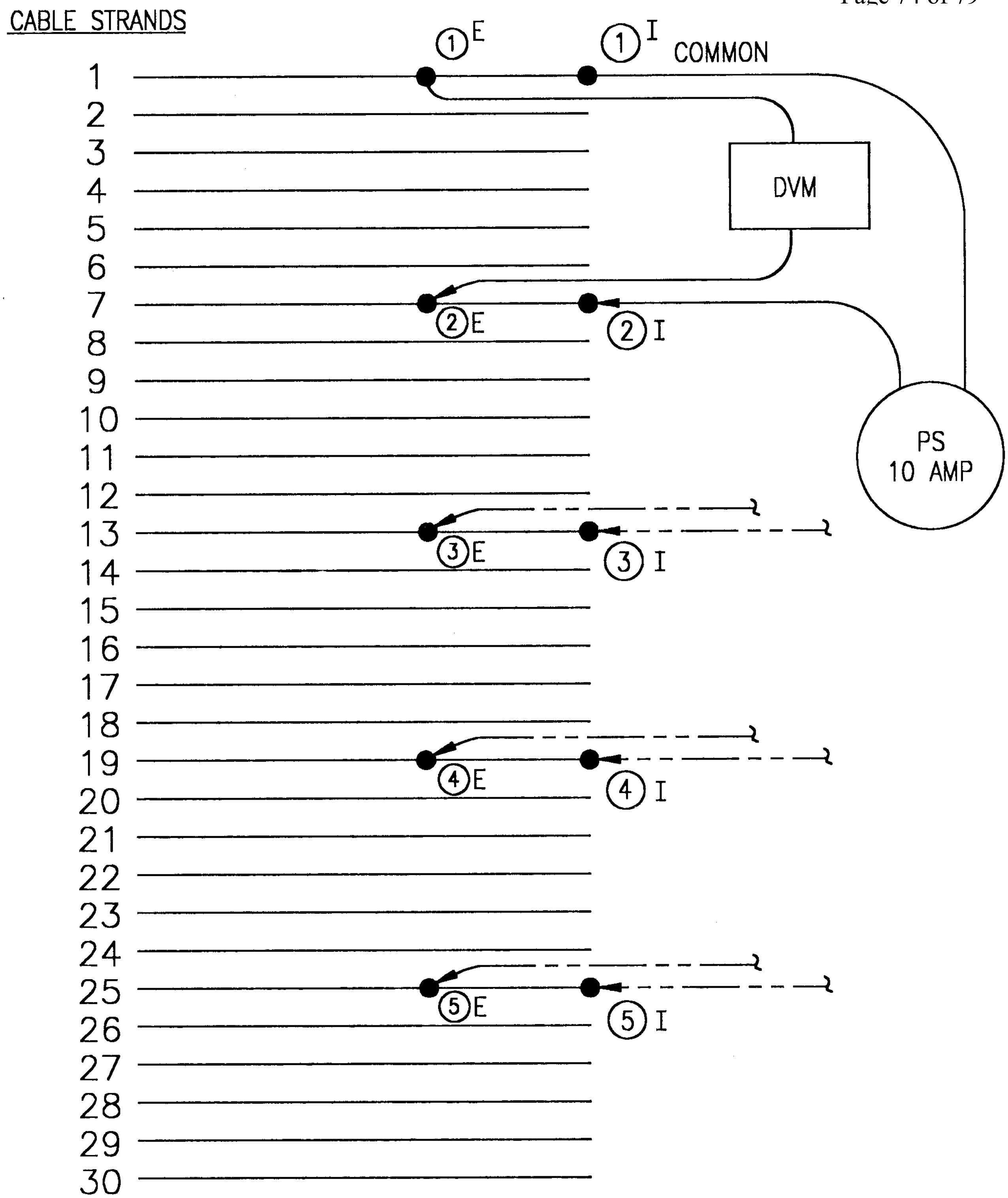

POWER SUPPLY AND DVM CONNECTIONS
WITH CONNECTION 1 AS COMMON.

FIGURE 4141-5 #3

Applied Pressure vs. Interstrand Resistance

(Typical Values)

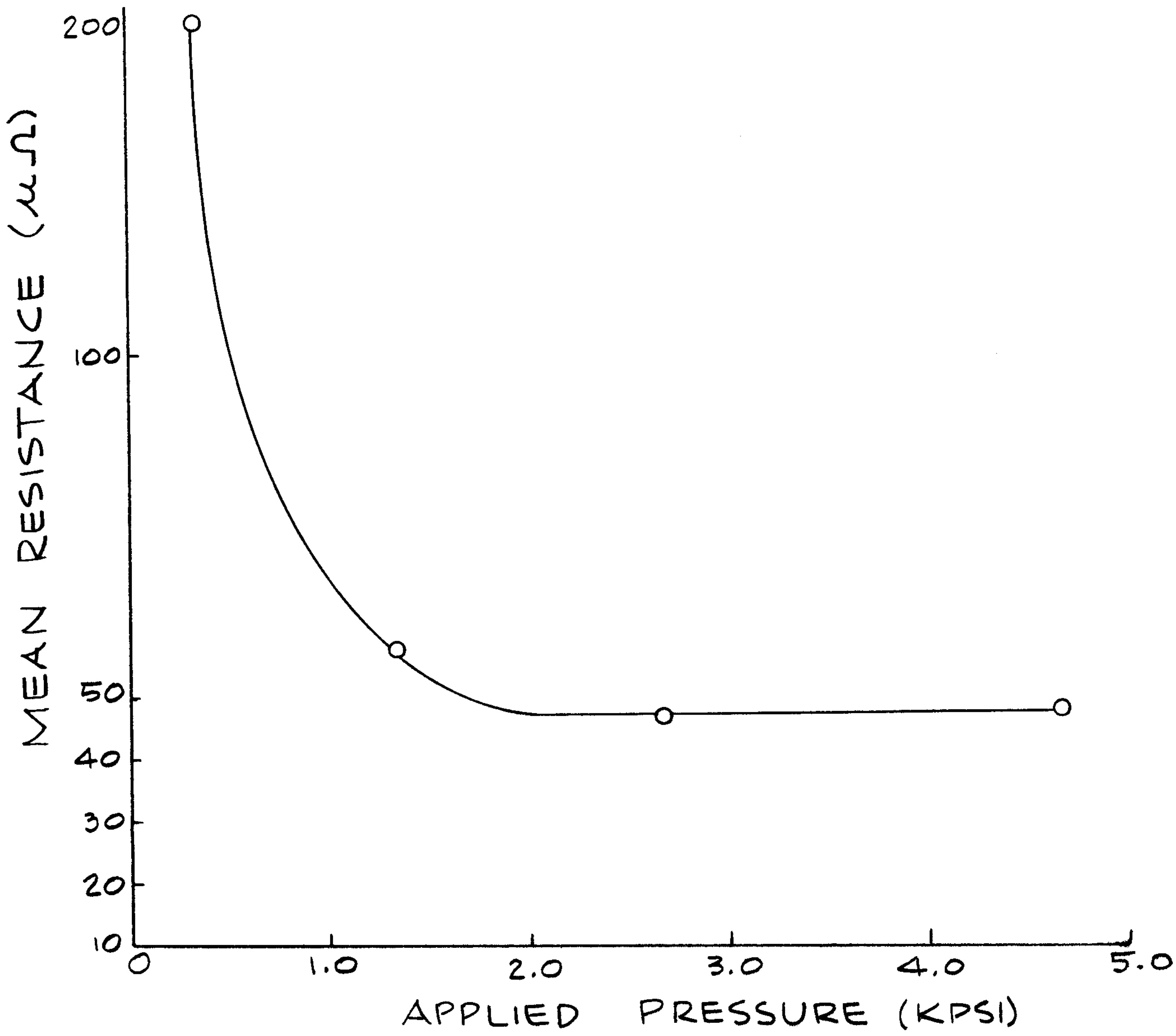

FIGURE 4141-5#4

APPENDIX C
WIRE AND CABLE MEASUREMENT DATA

On the sheets to follow are summarized the data transmittal for measurement information from the vendor to BNL. It is only necessary for the vendor to supply the data as given in Appendix A. The vendor will coordinate with BNL the regular transmittal in electronic form either on 3-1/2 inch or 5-1/4 inch floppy discs in any density. The file structures listed below can easily be imported into R:Base at BNL and are listed in order of preference.

1. R:Base
2. ASCII delimited
3. ASCII fixed
4. Lotus 1-2-2 (.WKS)
5. Excel (.XLS)
6. dBASE (.DBF)
7. pfs:FILE
8. DIF
9. Multiplan (SYLK)
10. Another system to be agreed upon by BNL

The 3-1/2 inch or 5-1/4 inch floppy discs from the Cable Measuring Machine (CMM) must be delivered in their usual format.

APPENDIX C (Cont'd)

Wire Mechanical Data

Wire ID
Wire twist direction (Left/Right)
Wire twist pitch (twists per inch)
Sharp bend test (Pass/Fail with comment)
Springback (degrees)
Surface condition (Pass/Fail with comment)
Cu/Sc ratio by chemical method (if used)
Comments

Wire Electrical Data

Wire ID
Date of tests
Run number
Ic at 3.0T
Ic at 5.0T
n at 3.0T
n at 5.0T
Iq at 3.0T
Iq at 5.0T
Jc at 3.0T
Jc at 5.0T
R(295)
RRR
Cu/Sc ratio by electrical method
Comments

Wire Production Data by Vendor

Wire ID
Wire length (feet)
Wire weight (lb.)
Diameter - Minimum
Diameter - Maximum
Diameter - Average
Diameter - Standard deviation
Diameter - Data points
Comments

APPENDIX C (Cont'd)

Cable Off-Line Mechanical Data

Cable ID
Sample ID (Hub, Lead, ...)
Mid-thickness by 10-stack method (inches)
Cable lay direction (Left/Right)
Cable lay pitch (inches)
Wire twist direction in cable (Left/Right)
Wire twist pitch in cable (twists per inch)
Cable residual twist (± degrees)
Bend test (Pass/Fail with comment)
Filament condition (Pass/Fail with comment)
Surface condition (Pass/Fail with comment)
Comments

Cable Measuring Machine Data

Cable ID
Cabling date
Cable measuring machine number
Cabling machine number
Pressure - Minimum
Pressure - Maximum
Pressure - Average
Pressure - Standard deviation
Pressure - Data points
Keystone - Minimum
Keystone - Maximum
Keystone - Average
Keystone - Standard deviation
Keystone - Data points
Width - Minimum
Width - Maximum
Width - Average
Width - Standard deviation
Width - Data points
Thickness - Minimum
Thickness - Maximum
Thickness - Average
Thickness - Standard deviation
Thickness - Data points
Comments

APPENDIX C (Cont'd)

Wire to Cable Data - Used to indicate in which cable(s) a wire is used

Cable ID
Cabler spool number
Wire ID
Starting cable location of wire (cable feet)
Ending cable location of wire (cable feet)
Wire piece length (wire feet)
Comments